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Competitive Effects of Trembling Aspen on Lodgepole Pine Performance in the SBS and IDF Zones of the Cariboo–Chilcotin Region of South-central British Columbia

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British Columbia
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ABSTRACT

A retrospective study was carried out between 1992 and 1999 in the Cariboo–Chilcotin area of the Southern Interior Forest Region[1] to quantify the effects of trembling aspen competition on lodgepole pine performance and to identify competition indices or other measures of competition that could be used by field staff. In six stands in the Sub-Boreal Spruce (SBS) dw1 and Interior Douglas-fir (IDF) dk3/dk4 biogeoclimatic variants, target pine were selected across neighbourhoods with varying densities of tall aspen (i.e., aspen as tall or taller than the target pine). Data pertaining to pine size and condition, and to the size and location of aspen within a 1.78-m radius of the target pine, were collected three times. Measurements commenced when stands were 7–12 years old. Various approaches were used to identify levels of aspen abundance where pine performance declined below acceptable levels. These included analyses of regression and correlation, tests of existing competition indices, and visual and statistical characterization of trends.

Tall aspen within a 1.78-m radius were the main contributors to reduced growth and vigour of target lodgepole pine, which suggests competition was mainly for light. Tall aspen density was the measure of aspen abundance that was most strongly correlated with pine size; when pine were 15–19 years old, this measure explained 48–64% of the variation in stem diameter in the SBSdw stands and 50–63% of the variation in the IDFdk stands. The most successful competition indices (CIs) for predicting pine diameter were based on the relative stem diameters of pine and aspen. The Navratil and MacIsaac CI explained 62–77% of pine stem diameter variation in the SBSdw stands and the Lorimer CI explained 51–59% of the variation in IDFdk stands.

In the SBSdw stands, ANOVA and visual interpretation of the data consistently showed that pine performance declined where tall aspen density exceeded 1000 tall aspen stems per hectare (1 tall aspen stem within a 1.78-m radius of target pine). Trends in IDFdk stands were less distinct, possibly because the effects of competition were being expressed more slowly. Pine diameter growth and vigour in IDFdk stands declined over a range of 2000–5000 tall aspen stems per hectare. We make conservative recommendations for the retention of aspen within pine stands in the Cariboo–Chilcotin SBSdw1 and IDFdk3/dk4 variants.

1 The Cariboo, Kamloops, and Nelson Forest Regions were consolidated into the Southern Interior Forest Region on April 1, 2003. The old “Cariboo Forest Region” is now generally referred to as the “Cariboo-Chilcotin area of the Southern Interior Forest Region.”

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1 INTRODUCTION

Strategies for managing mixed broadleaf–conifer stands in British Columbia have been under review in recent years. We have learned more about the role of broadleaves in forest ecosystems, and management objectives have also changed. In the past, broadleaves were viewed mainly as weeds that competed with conifers, and their presence was reduced as much as possible through the application of aggressive site preparation and brushing treatments. Many benefits of preserving a broadleaf component within stands are now recognized, but silviculturists require information about threshold levels of broadleaves that can be retained without incurring a serious negative effect on conifer performance.

Trembling aspen (*Populus tremuloides*) is a common component of forests throughout interior British Columbia, particularly in north and central areas of the province. In the Cariboo–Chilcotin area of the Southern Interior Forest Region, aspen commonly regenerates along with planted and natural lodgepole pine (*Pinus contorta* var. *latifolia*) in the Sub-Boreal Spruce (SBS), Interior Douglas-fir (IDF), Sub-Boreal Pine–Spruce (SBPS), and Interior Cedar–Hemlock (ICH) biogeoclimatic zones (Meidinger and Pojar 1991). Competition in aspen–lodgepole pine and aspen–white spruce (*Picea glauca*) stands has been studied in boreal ecosystems, but it is not known whether these results can be extrapolated to other climatic regions, or even applied across single biogeoclimatic zones in the same region.

High densities of aspen can reduce light to levels where conifer growth is limited for at least part of the growing season (DeLong and Tanner 1996; Coopersmith et al. 2000; Comeau 2002). Conifers growing among aspen are also commonly damaged by the "whipping" effect of nearby branches (Lees 1966). Light availability is of particular importance to lodgepole pine because of its low shade tolerance (Klinka and Scagel 1984b); studies have shown stem diameter growth decreases, height-to-diameter ratio increases, and crown width decreases where light is limited (e.g., Simard et al. 2001). In low light environments, lodgepole pine is known to allocate more growth to terminal shoots than lateral shoots, and to reduce branch number (Chen et al. 1996).

At low densities, aspen is beneficial to both individual conifers and the site as a whole. Young aspen trees take up large amounts of nutrients, particularly calcium, and retain them within the ecosystem (Pastor 1990). Aspen is also more resistant to *Armillaria* and *Phellinus* than most conifers, and its presence slows the spread of these root diseases through conifer stands (Morrison et al. 1991; Peterson and Peterson 1995; Gerlach et al. 1997). Young conifer seedlings may experience less frost damage under mature aspen canopies than in clearcuts (DeLong et al. 2000) because of reductions in nighttime radiative heat loss (Stathers 1989). Finally, because of its communal root system, sucker-origin aspen is mechanically stable (Strong and La Roi 1983), which may reduce windthrow among neighbouring conifers (Frivold 1985; Yang 1989).

Studies have shown that conifer growth is improved by reducing aspen abundance to levels where it is no longer a strong competitor (e.g., Yang 1989; Coopersmith and Hall 1999; Simard et al. 2001), but the magnitude of response has not been consistent, showing variation with both ecosystem and conifer species. Various competition indices have been tested for their ability to predict conifer performance on the basis of aspen abundance (e.g., Daniels 1976; Lorimer 1983; Navratil and MacIsaac 1993), and there have also been efforts to identify competition thresholds based on density and percent cover of aspen (Simard et al. 2001). Competition indices should be tested on an ecosystem-specific basis, however, because climatic variation may affect the intensity of some of the interactions between pine and aspen. In addition, competition indices developed for operational use should not only be good predictors of crop tree growth, they should also use data that are relatively easy to collect.

To investigate competition between trembling aspen and lodgepole pine and to study the effects of retaining aspen within young conifer stands, a retrospective study was initiated near Williams Lake, B.C. in 1992. Combinations of aspen and pine are the most common broadleaf–conifer mixtures in the Cariboo–Chilcotin area, and at the time this study was initiated, it was standard practice to clear all aspen from lodgepole pine plantations. Silviculturists were willing to prescribe alternative treatments, but they needed information about potential treatment effects on conifer crop trees across different ecosystems.

The SBS and IDF zones were selected for study because of the widespread occurrence of pine–aspen stands in these zones. Although pine–aspen stands are also common in the SBPS and ICH zones, low productivity in the former and diverse species combinations in the latter made them less appropriate for study. The study was designed to characterize correlations between aspen density and lodgepole pine performance in the Horsefly variant of the Dry Warm SBS (SBSdw1) and the Fraser and Chilcotin variants of the Dry Cool IDF (IDFdk3 and IDFdk4) (Steen and Coupé 1997), which typify conditions of the Cariboo–Chilcotin moist transition and dry-belt, respectively.

The study was also intended to adapt and test competition indices that had been developed by other researchers for use in pine–aspen stands. Retrospective data were collected in three separate assessments that were carried out between 1992 and 1999. Seven-year results are summarized in this working paper, which is intended to provide forest managers with guidance regarding levels of aspen that can be retained in managed plantations without seriously reducing lodgepole pine growth and vigour.

In summary, the objectives of this research were:

1. To quantify the effects of trembling aspen competition on lodgepole pine performance in the SBSdw1 and IDFdk3/dk4 variants in the Cariboo–Chilcotin area of the Southern Interior Forest Region, over a range of aspen densities.
2. To identify measurements of aspen competition that can easily be obtained by field staff.
3. To investigate the usefulness of competition indices developed by other researchers for assessing competition in young pine–aspen stands in the Cariboo–Chilcotin region.
4. To investigate size of the competitive neighbourhood around lodgepole pine, over a range of aspen densities.

2.1 Study Areas and Site Selection

Six sites were selected for this study: three in the SBSdw1 and three in the IDFdk3/dk4 (Figure 1). Potential sites were identified by screening the Cariboo Forest Region[2] silviculture records database for 5- to 15-year-old cutblocks in these variants that had naturally regenerated to pine–aspen mixtures. Sites were visited to determine whether they met the following criteria:

- pine were 7–12 years old (the age when decisions are generally made about applying brushing treatments to meet free-growing obligations);
- pine–aspen mixtures covered at least 2 ha;
- aspen trees were present in a range of canopy cover classes;
- aspen densities reached at least 4000 stems per hectare in some areas of the site; and
- the study area was homogeneous in ecological characteristics and treatment history.

Environmental characteristics of the study sites are summarized in Table 1, and logging and treatment history is presented in Table 2. A small amount of paper birch was present on the SBSdw sites, but for purposes of analysis and reporting, stands were considered to be pure aspen (i.e., birch stems were included in the analysis as aspen). Each site was homogeneous with regard to slope, aspect, moisture regime (submesic to subhygric), nutrient regime (medium), and soil characteristics. Zonal soils are brunisolic in the SBS zone and luvisolic in the IDF zone (Steen and Coupé 1997). Herb

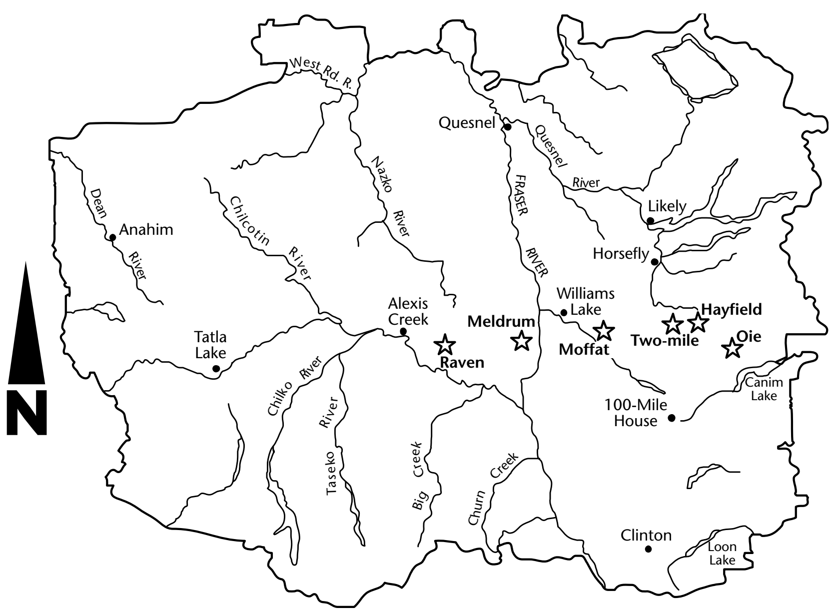


FIGURE 1 *Location of retrospective study sites in the Cariboo–Chilcotin area of the Southern Interior Forest Region.*

2 When this project was initiated, the study sites were part of the Cariboo Forest Region. This region was incorporated into the Southern Interior Forest Region on April 1, 2003.

TABLE 1 *Environmental characteristics of the study sites*

	Two-mile	Hayfield	Oie Lake	Moffatt	Meldrum	Raven
Map sheet and opening number	93A004-35	93A004-15	92P094-41	93A001-30	93B009-31	92O096-208
Biogeoclimatic classification	SBSdw1/01	SBSdw1/01	SBSdw1/01	IDFdk3/01	IDFdk3/01	IDFdk4/01
Elevation (m)	1025	1097	1100	1045	900	1200
Aspect	Variable (gently undulating terrain)	Variable (gently undulating terrain)	North to northeast	Generally flat with a slight west aspect	Generally flat with a slight west aspect	Variable (gently undulating terrain)
Slope (%)	0–10	0–10	0–20	0–5	0–5	0–5
Moisture regime[a]	Mesic (submesic, subhygric)	Mesic (submesic)	Mesic (subhygric)	Mesic	Mesic	Mesic (submesic)
Mean annual precipitation (mm)[b]	585	585	585	433	433	355
Mean annual temperature (°C)[b]	3.7	3.7	3.7	3.3	3.3	2.8
Frost-free days[b]	152	152	152	151	151	122

a Moisture regimes in parentheses occurred in isolated patches within the study areas.
b Based on Steen and Coupé (1997).

TABLE 2 *Logging and treatment history of the study sites*

	SBSdw			IDFdk		
	Two-mile	**Hayfield**	**Oie Lake**	**Moffatt**	**Meldrum**	**Raven**
Date of clearcut logging	1977	1978	Summer 1983	1981	Summer 1980	Summer 1983
Method and date of site preparation	None	None	None	None	None	None
Estimated age of natural pine at the start of the study[a]	11 years	10 years	7 years	8 years	12 years	8 years
Other treatments	None	None	Brushing 1994	Mistletoe eradication 1984	None	Mistletoe eradication 1987 Brushing 1998

a Approximate lodgepole pine age was determined by counting branch whorls.

and shrub cover were reasonably homogeneous across each of the sites, and the species present were typical for the respective biogeoclimatic units (Steen and Coupé 1997). Mean herb cover ranged from 23–29% on the SBSdw sites and 15–29% on the IDF sites. Shrub cover was somewhat higher on the SBSdw sites (15–18%) than the IDFdk sites (6–11%).

2.2 Sampling Design

This was a retrospective study that investigated natural patterns within the lodgepole pine–trembling aspen community and, as such, no treatments were applied. Initial sampling in both the SBSdw and IDFdk study areas took place in 1992, using a systematic-random approach to select target pine growing within a representative range of aspen environments. To accomplish this, a transect was established through the stand at each site, and every acceptable pine within 5 m on either side of the transect was assigned to one of seven aspen cover classes (based on ocular estimates of the percentage of ground surface covered by aspen): 0, 1–5, 6–10, 11–15, 16–20, 21–25, and ≥ 26%. Sampling continued until a total of 50 pine had been selected, and therefore the transects were of varying length from site to site. To be considered "acceptable", pine had to be free of damage (except competition effects) and free of competition from other conifers (i.e., the crown did not overlap that of other conifers and no other conifer stems occurred within a 1-m radius). The pine also had to be of an age to suggest they had naturally regenerated within five years following harvest. Approximate age, which was considered adequate for our purposes, was determined by counting branch whorls (although some false whorls were present, they were usually easy to identify). The 50 target pine selected at each site also had to be distributed as evenly as possible among the aspen cover classes. On some sites, aspen cover did not exceed 20%. In these cases, the pine selected were distributed as evenly as possible among the remaining classes. Aspen cover did not exceed 40% on any of the sites, even when densities exceeded 35 000 stems per hectare. Once a particular cover class had approximately the right number of target pine, additional pine in that class were passed over. All target pine were tagged and mapped for future relocation.

Initial data analysis revealed that lodgepole pine growth was more strongly correlated with aspen density than percent cover. It also revealed that pine growth was negatively affected at aspen densities of less than 5000 stems per hectare. However, relatively few target pine had been selected below this density, even in the lowest aspen cover class. For this reason, and because other studies were focusing primarily on aspen density as a measure of abundance, we decided to increase the number of target pine in low density aspen neighbourhoods. Additional pine were selected in 1994 on the SBSdw study sites and in 1997 on the IDFdk sites. The use of aspen cover classes was discontinued at this point, and target pine were re-assigned to one of the following density classes defined by the number of aspen as tall or taller than the target pine (hereafter called "tall aspen"): 0, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, and ≥ 10 000 stems per hectare. These densities corresponded to 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, and ≥ 10 tall aspen stems in each 10-m^2 (1.78-m radius) plot. Sample sizes in tall aspen density classes in 1992, 1994, 1997, and 1999 are shown in Table 3. Appendix 1 contains a full list of plots measured in each year at each site.

2.3 Measurements

Three full sets of measurements were collected at each site between 1992 and 1999. On SBSdw sites, measurements were done in 1992, 1994, and 1999. On IDFdk sites, measurements were done in 1992, 1997, and 1999 (Table 4).

TABLE 3 *Sample sizes[a,b,c] in tall aspen density classes in different measurement years in the SBSdw and IDFdk subzones*

	Tall aspen density[d]										
Stems per plot	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**≥ 10**
Stems per hectare	**0**	**1000**	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**≥ 10 000**
SBSdw											
1992	28	2	7	8	11	10	13	7	8	5	53
1994	19	15	21	16	23	19	12	10	8	11	39
1999	20	11	13	14	13	19	9	7	4	6	10
IDFdk											
1992	11	6	6	4	10	2	8	9	6	5	82
1997	19	17	19	13	18	8	8	7	10	6	57
1999	14	8	12	10	11	5	5	10	9	5	28

a Sample sizes in 1992 show the number of target pine initially selected in each tall aspen density class. Sample sizes in 1994, 1997, and 1999 reflect the selection of additional target pine in low-density classes in 1994 and 1997, as well as changes resulting from target pine mortality and fluctuations in the relative height of pine and aspen (i.e., if aspen were growing faster than pine, the number of tall aspen could increase between assessment years, shifting the plot into a different class).

b The Oie Lake and Raven sites were not measured in 1999, resulting in a reduction in sample sizes from 1994 (SBSdw) and 1997 (IDFdk).

c See Table A1.1 and Table A1.2 in Appendix 1 for a full list of plots measured in each year at each site.

d Tall aspen density classes include only aspen as tall or taller than the target pine.

Vegetation data were collected in July and August, and pine and aspen data were collected between mid-August and the end of September, after the termination of annual pine height growth. Assessments after 1992 included both the original and low-density plots; however, the Oie Lake (SBSdw) and Raven (IDFdk) sites were dropped before the 1999 assessment because they had been returned to the operational forestry program. Table 4 provides all assessment dates.

2.3.1 Target Lodgepole Pine The following measurements were made on target lodgepole pine in all assessments:

- Total height (cm)
- Leader length (cm)
- Basal stem diameter (cm)
- Crown width (average of N–S and E–W widths) (cm)
- Crown length (cm)

Height-to-diameter ratio (HDR) and height and stem diameter growth increments during specific time periods were calculated. Pine vigour (rated as good, fair, poor, moribund, or dead), damage, and damage cause were assessed according to standard Cariboo Region Research protocol (Appendix 2).

2.3.2 Neighbourhood Measurements Measurements to assess the effects of neighbourhood competition on target lodgepole pine were done in 1.78-m-radius (10 m^2) plots around the target pine, and they were mainly concerned with trees rather than understorey vegetation. To assess the effects of competition in larger neighbourhoods and to allow comparison of our results with other studies, the 1999 assessment included additional measurements in plots of a 2.52 m (20 m^2) and a 3.99 m (50 m^2) radius. Measurements in the larger plots were done in a randomly selected subset of plots at each site, and included three plots in each of the 0, 1000, 2000, 3000, 4000, and 5000 stems per hectare aspen density classes, and two plots in each of the 6000, 7000, 8000, 9000, and ≥ 10 000 classes. The three plot sizes were nested, and centred on the target pine. Lower-density classes were sampled more intensively because thresholds for operationally acceptable pine performance were clearly in the range of 1000–5000 tall aspen stems per hectare.

At each assessment date, the following measurements were recorded for all trees (broadleaves and conifers) in the plot around each target pine:

- Height (cm)
- Basal stem diameter (cm)
- Stem-to-stem distance (cm) (i.e., the distance from the outside edge of the neighbourhood tree stem to the stem centre of the target pine)
- Crown-to-stem distance (cm) (i.e., the distance from the crown edge of the neighbourhood tree to the stem centre of the target pine). If the crown of the neighbourhood tree had grown directly over the leader of the target pine, the distance was measured back to the target pine stem centre, and recorded as negative.

An ocular estimate of percent ground cover of each tree species was recorded in 1992. In 1999, the presence of aspen clumps was recorded. Individual aspen stems were considered part of a clump when they were ≤ 30 cm

TABLE 4 *Timing of study activities on SBSdw and IDFdk sites*

Year	SBSdw sites	IDFdk sites
1992	• Identification of target pine based on aspen cover classes • Target pine measurements • Neighbourhood tree measurements, including cover • Neighbourhood vegetation height and cover • Light measurement	• Identification of target pine based on aspen cover classes • Target pine measurements • Neighbourhood tree measurements, including cover • Neighbourhood vegetation height and cover • Light measurement
1993	• Target pine measurements	• Target pine measurements
1994	• Selection of additional target pine in areas of low aspen density • Designation of previously selected pine into aspen density classes • Target pine measurements • Neighbourhood tree measurements (tall aspen and pine only)	
1995	• Target pine measurements	• Target pine measurements
1996		• Target pine measurements
1997		• Selection of additional target pine in areas of low aspen density • Designation of previously selected pine into aspen density classes • Target pine measurements • Neighbourhood tree measurements (tall aspen and pine only)
1999	• Oie Lake site dropped • Target pine measurements • Neighbourhood tree measurements, including assessment of aspen clumping • Neighbourhood tree measurements in 20- and 50-m^2 plots	• Raven site dropped • Target pine measurements • Neighbourhood tree measurements, including assessment of aspen clumping • Neighbourhood tree measurements in 20- and 50-m^2 plots

from another aspen stem (outside-stem to outside-stem at a height of 30 cm). Density and basal area were calculated for aspen.

2.3.3 Additional Vegetation Measurements In 1992 only, the following measurements were recorded to characterize the site, and to determine whether a correlation existed between the abundance of herbs and shrubs and the size of lodgepole pine:

- Percent cover and modal height (cm) of the shrub layer
- Percent cover and modal height (cm) of the herb layer
- Percent cover and modal height (cm) of individual shrub and herb species having ≥ 15% cover

2.3.4 Light Measurements In 1992 only, light under the aspen canopy was measured using two Sunfleck ceptometers. Measurements of photosynthetically active radiation (PAR) were recorded simultaneously on north and south sides of the target pine. Readings were taken at two-thirds of the tree's total height to avoid shade from lower vegetation. A third ceptometer, controlled by an operator in radio contact with the understorey operators, was employed to take simultaneous measurements in full sunlight. This measurement was used to calculate the percent of total available sunlight at each target pine. All light measurements were taken on clear days in mid-August, between 9:45 am and 1:30 pm.

2.4 Analysis

SAS statistical software (SAS Institute Inc. 1996, 1999) was used for all data analyses. Before analysis, data were checked for outliers and normality using PROC UNIVARIATE. Summary statistics were compiled using PROC TABULATE, correlation analysis was carried out with PROC CORR, and regression analysis was done with PROC NLIN. Analysis of variance was done with PROC GLM (for balanced data only) and PROC MIXED.

Correlation and Regression Analysis Twenty individual measures of vegetation abundance (numbers 1–20 below) were tested for their correlation with lodgepole pine size (stem diameter, height, and leader length). Analysis was carried out for the two subzones (SBSdw and IDFdk), and for individual sites in the SBSdw (Hayfield, Two-mile, and Oie Lake) and IDFdk (Moffatt, Meldrum, and Raven) using data collected in the 10-m^2 plots in 1992 and 1993. As we expected aspen to be a more important competitor with lodgepole pine than other vegetation, the first run of correlation analysis was designed to determine whether all aspen stems were contributing to competition, or only those stems taller than a certain height. To accomplish this, aspen in each plot were assigned to the following relative height classes:

- < 50% as tall as the target pine
- ≥ 50% as tall as the target pine
- ≥ 75% as tall as the target pine
- ≥ 100% as tall as the target pine

Spearman's rank correlation coefficients were calculated for pairings of aspen abundance variables with lodgepole pine size variables. Because the highest correlation consistently occurred when only aspen as tall or taller than the target pine (≥ 100% as tall as the target pine) were included in the data set, subsequent calculation of aspen-related variables included only "tall aspen," unless otherwise stated. Comparison of Spearman's rank correlation coefficients for individual sites, and examination of the associated scatter plots, revealed that the relationship between aspen and pine varied noticeably between sites within each subzone. For this reason, subsequent correlation and regression analyses were carried out on an individual-site basis.

The following 20 variables were evaluated for each site by calculating Spearman's rank correlation coefficients and examining scatter plots of the data. Aspen of all heights were included in the estimation of "total aspen cover" (variable number 5), but only tall aspen were included in the calculation of all other aspen-related variables (variables 8–20).

1. Shrub cover
2. Shrub height (modal)
3. Herb cover
4. Herb height (modal)
5. Total aspen cover
6. Conifer cover
7. Total tree cover (all broadleaf and conifer trees)
8. Tall aspen density
9. Σ (sum of) tall aspen basal area
10. Σ stem-to-stem distance (sum of the distances from the target pine stem to each tall aspen stem)
11. Mean stem-to-stem distance (mean distance from the target pine stem to tall aspen stems)
12. Minimum stem-to-stem distance (minimum distance from the target pine stem to a tall aspen stem)
13. Σ stem-to-crown distance (sum of the distances from the target pine stem to the closest edge of each tall aspen crown)
14. Mean stem-to-crown distance (mean distance from the target pine stem to the closest edge of the tall aspen crowns)
15. Minimum stem-to-crown distance (minimum distance from the target pine stem to the closest edge of a tall aspen crown)
16. Mean tall aspen height
17. Maximum tall aspen height
18. Mean tall aspen diameter
19. Maximum tall aspen diameter
20. Diameter of tallest aspen

Variables that showed the strongest relationship with pine size were selected for further study with regression analysis. Based on results from the initial screening of the 20 vegetation variables, we determined that tall aspen density was the measure of vegetation abundance that was most highly correlated with the four lodgepole pine variables (1992 stem diameter, 1992-1993 diameter increment, 1992 height, and 1992 leader length). Scatter plots of the data indicated that the aspen-pine relationships were not linear, so several non-linear models were considered. The non-linear models that provided the best visual fits were further examined by calculating the coefficient of determination (R^2).[3] The best fit was consistently provided by Equation (1):

$$y = ae^{bx} + \varepsilon, \qquad (1)$$

where: y is one of the pine growth variables, x is the aspen abundance variable, ε is the residual error (assumed to be independent, with the same normal distribution for all plots), a and b are model parameters estimated for each site by the (non-linear) least-squares method, and e is the base of the natural log (ln) and is equal to 2.71828. The relationship between tall aspen density and lodgepole pine size was also examined using data collected in 1999. Spearman's rank correlation coefficients were calculated and Equation (1) was fitted for pairings of tall aspen density with 1992–1999 pine stem diameter growth and 1999 leader length. Analyses were carried out for two sites in each of the SBSdw and IDFdk subzones, using data collected in 10-m^2

3 R^2 was calculated as $[1 - (SS_r/SS_c)]$, where SS_r is the residual sum of squares and SS_c is the corrected sum of squares.

plots. Data from the Oie Lake and the Raven study sites were not included because they had been dropped before the 1999 assessment.

Correlation and regression analyses were also used to examine the ability of the competition indices (CIs) listed in Table 5 to predict lodgepole pine size. Spearman's rank correlation coefficients were calculated for pairings of pine growth variables (1992 pine stem diameter, 1992–1993 diameter increment, and 1992 leader length) with CIs for the six individual SBSdw and IDFdk sites, using data collected in 1992 and 1993 in 10-m^2 plots. The original indices developed by other researchers had not necessarily involved aspen or used 10-m^2 plots, but they were adapted to fit the requirements of this study (Table 5).

Based on results from our correlation analyses, the five CIs that were most strongly correlated with lodgepole pine growth (numbers 1–5 in Table 5) were selected for further regression analysis. The ability of these CIs to predict lodgepole pine stem diameter, diameter increment, and leader length was tested by fitting Equation (1). Four of the five CIs contained a pine size variable, and therefore had the potential to artificially inflate the correlation; only the Simard CI did not include some measure of pine size among the independent variables. Although CIs that do not have a built-in degree of correlation with pine size are better predictors of competition levels, those that contain both aspen and pine variables illustrate relative size relationships, which can be useful for operational purposes.

Using data collected in 1999 at two SBSdw sites (Hayfield and Two-mile) and two IDFdk sites (Moffatt and Meldrum), the size of the neighbourhood in which aspen were competing with lodgepole pine was investigated. Using the subset of plots in which data were collected in three plot sizes (Section 2.3.2), three sets of Spearman's rank correlation coefficients (one for each plot size) were calculated for each pairing of a pine variable (1992–1999 diameter increment or 1999 leader length) with tall aspen density. Coefficients for the different plot sizes were then compared to determine whether the correlation increased or decreased as neighbourhood size increased.

TABLE 5 *Competition indices tested in this study*

	Competition index	Source
1.	(aspen % cover × mean aspen height) / target pine height	Comeau, Braumandl, Xie (1993)
2.	diameter of tallest aspen / target pine diameter	Navratil and MacIsaac (1993)
3.	∑ (aspen height / pine–aspen stem-to-stem distance)[a]	Simard (1990)
4.	∑ (aspen diameter / target pine diameter)[a]	Lorimer (1983)
5.	∑ [(aspen diameter / target pine diameter) / pine–aspen stem-to-stem distance][a]	Daniels (1976)
6.	% aspen cover / (distance to nearest aspen)^2	Wagner and Radosevich (1987)
7.	(mean aspen height / target pine height) × [(mean pine–aspen stem-to-stem distance / target pine crown radius) + 1]$^{-1}$ × aspen % cover	Brand (1986)
8.	(mean aspen height × aspen % cover) / mean stem-to-crown distance	DeLong (1991)
9.	(mean aspen height × aspen % cover) / mean pine–aspen stem-to-stem distance	Modification of DeLong (1991)
10.	∑ [(aspen height – target pine height) / pine–aspen stem-to-stem distance] [a]	Braathe (1989)

a The summation symbol (Σ) indicates that values within the outermost set of parentheses were summed for each 10-m^2 plot.

Correlation analysis was also used to determine whether aspen growing in clumps should be considered as several individual trees or as a single tree. Spearman's rank correlation coefficients were calculated for pairings of pine growth variables (1992–1999 diameter growth or 1999 leader length) with "clumped" or "individual" tall aspen density. The pine growth variables selected for testing were those that had been highly correlated with tall aspen density in the 10-m^2 plots. For "clumped" tall aspen density, clumps of aspen were considered as one tree; for "individual" tall aspen density, each stem was considered as one tree. The analysis of clumping effects was carried out using data collected in all three plot sizes.

Lastly, correlation analysis was used to examine the relationship between light availability under the aspen canopy and lodgepole pine growth. Using 1992 data, Spearman's rank correlation coefficients were calculated for pairings of percent available light with lodgepole pine growth variables.

Analysis of Variance (ANOVA) Mixed-model ANOVA was used to determine whether differences in tall aspen density affected target pine growth in 1992, 1994, and 1999 for SBSdw sites and in 1992, 1997, and 1999 for IDFdk sites (Table 6). The Raven and Oie Lake sites, which were dropped before the 1999 assessment, were excluded from the analysis for all years, leaving two sites per zone. By using the four sites that were measured in all assessments from 1992 through 1999, we were able to identify trends in pine–aspen competition over time. It was not possible to use time as a factor in the analysis because the same pine were not necessarily included in the same tall aspen density classes from year to year. Pine moved from class to class as a result of:

- changes in aspen density as the stands matured,
- pine mortality,
- changes in the height of aspen relative to pine, and
- the addition of pine in lower tall aspen density classes in 1994 (SBSdw) and 1997 (IDFdk) (refer to Table 3).

TABLE 6 *Analysis of variance (ANOVA) table for examining the effects of tall aspen density on lodgepole pine growth*

Source of variation	Degrees of freedom[a,b]	Type of effect
Zone (Z)	2 – 1 = 1	Fixed
Site (per zone) (S)[c]	(2 – 1) × 2 = 2	Random
Aspen density (D)	11 – 1 = 10	Fixed
$Z \times D$	1 × 10 = 10	Fixed
$D \times S(Z)$	10 × (2 – 1) × 2 = 20	Random
Tree	n – 44	Random

a The denominator degrees of freedom for testing the fixed effects of zone, density, and the zone × density interaction were calculated by Satterthwaite's approximation for unbalanced designs (because the number of live trees per density class varied across classes).

b *n* is the total number of live target pine.

c Only the Hayfield and Two-mile (SBSdw) and the Moffatt and Meldrum (IDFdk) sites were included in the analysis. The Oie Lake and Raven sites were dropped from the analysis for all years because they were not measured in 1999.

Least-squares means were calculated in the mixed model analysis (PROC MIXED) for each density class (averaging over zones) and for each zone (averaging over density classes). Multiple t-tests, in which the Bonferroni method was used to control the overall type I error, were used to compare individual class means and to identify groups of means that did not differ significantly.

3 RESULTS

3.1 Establishment of Tall Aspen Density Classes

Mean density of tall aspen in the original cover classes (see Section 2.2) was considerably higher on IDFdk than SBSdw sites (Table 7). For example, mean tall aspen density in the 1–5% cover class ranged from 440 to 1000 stems per hectare at the SBSdw sites, compared with 4500 to 7880 stems per hectare at the IDFdk sites. In the 6–10% cover class, mean tall aspen densities ranged from 4330 to 5330 stems per hectare at the SBSdw sites, compared with 9740 to 18 800 stems per hectare at the IDFdk sites. Other cover classes had differences of similar magnitude between the SBSdw and IDFdk sites.

3.2 Correlation and Regression Analysis Results

3.2.1 Predicting Lodgepole Pine Growth from Neighbourhood Vegetation Abundance Spearman's rank correlation coefficients were calculated for pairings of lodgepole pine size variables with each of 20 neighbourhood vegetation abundance variables, using data collected in 1992 (and 1993 for stem diameter increment) from the individual study sites in the SBSdw and IDFdk subzones. For each lodgepole pine size variable, coefficients for pairings with the 20 vegetation variables were ordered from greatest to least correlation and assigned ranking values of 1 to 20 (the greatest correlation received a ranking of 1 and the least received a ranking of 20). For each pairing of a pine and a vegetation variable, rankings for the three sites in each subzone were then summed (i.e., if, for predicting pine stem diameter in the IDFdk, tall aspen density had a ranking of 1 at Moffatt, 2 at Meldrum, and 5 at Raven, then the sum of the values would be $1 + 2 + 5 = 8$). The neighbourhood vegetation abundance variables that had the lowest sums were considered the best predictors of the various measures of pine size for the sites in each subzone.

Of the variables examined, tall aspen density was the one that was most strongly correlated with pine size at both SBSdw and IDFdk sites (Table 8). Stem diameter and leader length were negatively correlated with tall aspen density, and height was positively correlated. The shift from a positive height correlation to a negative leader length correlation suggests that pine height growth had increased in response to reduced light availability at an early age, and although the effects were still evident when pine were 7–12 years old (positive correlation for height), that growth strategy had ceased (negative correlation for leader length). Tall aspen density was consistently more strongly correlated with pine size than total aspen density. Other variables related to tall aspen density (e.g., Σ stem-to-stem distance, Σ stem-to-crown distance, and Σ aspen basal area) were also consistently among those most strongly correlated with pine size. Variables related to the size of individual aspen, or the spatial relationship between aspen and the target pine (e.g., mean or minimum stem-to-stem distance) were not as well correlated with pine size as the density-related variables. Variables relating to shrub and herb abundance were poorly correlated with pine size.

TABLE 7 *Number of plots (n) and mean[a] total and tall aspen densities (stems per hectare) in 5% cover classes in 1992*

	Aspen cover classes (%)						
	0	**1–5**	**6–10**	**11–15**	**16–20**	**21–25**	**≥ 26**
SBSdw							
Hayfield							
n	2	9	9	6	9	6	10
Tall aspen density	0 ± 0	440 ± 880	4 330 ± 2 350	6 330 ± 3 010	6 890 ± 2 670	10 000 ± 2 830	14 000 ± 5 030
Total aspen density	2 000 ± 1 000	2 890 ± 700	9 000 ± 1 610	10 830 ± 1 220	10 220 ± 1 270	16 500 ± 2 840	18 100 ± 2 070
Two-mile							
n	9	1	11	6	12	2	10
Tall aspen density	0 ± 0	0 ± 0	4 730 ± 1 680	4 000 ± 2 450	6 830 ± 4 690	6 000 ± 0	11 700 ± 4 740
Total aspen density	110 ± 110	2 000 ± 2 000	7 910 ± 840	10 170 ± 2 330	14 750 ± 2 360	11 000 ± 1 000	17 300 ± 3 000
Oie Lake							
n	7	4	3	5	8	5	18
Tall aspen density	0 ± 0	1 000 ± 1 410	5 330 ± 2 520	9 200 ± 3 270	11 500 ± 3 120	16 200 ± 4 710	20 390 ± 10 990
Total aspen density	1 570 ± 530	2 250 ± 630	9 670 ± 2 030	13 600 ± 2 250	18 500 ± 3 120	20 800 ± 3 310	25 780 ± 2 770
IDFdk							
Moffatt							
n	0	18	19	7	4	2	0
Tall aspen density	—	5 280 ± 3 530	9 740 ± 3 830	13 290 ± 2 290	17 750 ± 7 410	21 500 ± 4 950	—
Total aspen density	—	8 220 ± 1 280	15 050 ± 1 290	16 140 ± 670	22 250 ± 2 870	22 500 ± 4 500	—
Meldrum							
n	0	18	8	10	6	2	5
Tall aspen density	—	4 500 ± 5 060	14 380 ± 3 580	12 900 ± 6 470	11 670 ± 8 360	13 500 ± 4 950	22 000 ± 7 710
Total aspen density	—	10 500 ± 1 780	21 880 ± 1 990	22 100 ± 2 320	23 830 ± 4 840	25 000 ± 1 000	25 400 ± 5 100
Raven							
n	1	25	15	7	2	0	0
Tall aspen density	0 ± 0	7 880 ± 7 300	18 800 ± 12,630	23 000 ± 5 420	24 500 ± 6 360	—	—
Total aspen density	6 000 ± 6 000	13 880 ± 2 190	27 070 ± 3 720	34 000 ± 5 520	37 500 ± 6 500	—	—

a Values are presented in the form of "mean ± 1 standard error".

TABLE 8 *Ranges of Spearman's rank correlation coefficients (minimum to maximum across three sites) for the five neighbourhood vegetation abundance variables[a] that were most highly correlated[b] with lodgepole pine stem diameter, height, and leader length in each of the SBSdw and IDFdk subzones in 1992*

Stem diameter	R[c]	Height	R	Leader length	R
SBSdw		**SBSdw**		**SBSdw**	
Tall aspen density	–0.73 to –0.82	Tall aspen density	0.62 to 0.77	Tall aspen density	–0.25 to –0.73
Σ stem-to-stem distance	–0.72 to –0.80	Σ stem-to-stem distance	0.59 to 0.74	Σ stem-to-crown distance	–0.31 to –0.72
Σ stem-to-crown distance	–0.65 to –0.80	Total tree cover	0.62 to 0.70	Σ stem-to-stem distance	–0.25 to –0.72
Σ aspen basal area	–0.64 to –0.77	Σ aspen basal area	0.55 to 0.73	Total tree cover	–0.13 to –0.57
Total aspen cover	–0.57 to –0.74	Total aspen cover	0.62 to 0.70	Σ aspen basal area	–0.14 to –0.70
IDFdk		**IDFdk**		**IDFdk**	
Tall aspen density	–0.59 to –0.68	Total tree cover	0.44 to 0.55	Tall aspen density	–0.52 to –0.61
Σ stem-to-stem distance	–0.53 to –0.62	Tall aspen density	0.44 to 0.50	Σ stem-to-stem distance	–0.48 to –0.55
Σ stem-to-crown distance	–0.57 to –0.59	Σ stem-to-stem distance	0.37 to 0.48	Σ stem-to-crown distance	–0.47 to –0.58
Σ aspen basal area	–0.37 to –0.61	Total aspen cover	0.44 to 0.53	Σ aspen basal area	–0.44 to –0.47
Minimum stem-to-stem distance	0.28 to 0.60	Σ aspen basal area	0.36 to 0.56	Mean aspen diameter	0.26 to 0.50

a With the exception of total aspen cover, neighbourhood abundance variables involving aspen were calculated using tall aspen only.

b The top five competition variables were chosen for each pine variable in each subzone by summing the rankings from 1 to 20 for each competition variable across the three sites in each subzone, and selecting the smallest five values (see Appendix 3).

c *R* is the Spearman's rank correlation coefficient. Negative correlations improve as *R* decreases from 0 to –1; positive correlations improve as *R* increases from 0 to +1.

On the basis of consistently strong negative correlations between tall aspen density and lodgepole pine stem diameter and leader length, the relationship was further investigated using non-linear regression analysis (Figure 2). The R^2 values indicate tall aspen density explained 40–65% and 37–43% of the variation in 1992 pine stem diameter at the SBSdw (Table 9) and IDFdk sites (Table 10), respectively. Regression analyses for different years also suggest the relationship between tall aspen density and lodgepole pine stem diameter became stronger as the stands aged. When 1999 pine stem diameter was examined, tall aspen density explained 48–68% of the variation at the SBSdw sites and 50–63% of the variation at the IDFdk sites (Table 9, Table 10, Figure 2).

In 1992, when stands were 7–12 years old, tall aspen density was not as good a predictor of pine height and leader length as it was of stem diameter. The R^2 values were lower and also showed more variation from site to site. In 1999, when stands were 15–19 years old, relationships between density and pine height or leader length continued to vary between sites.

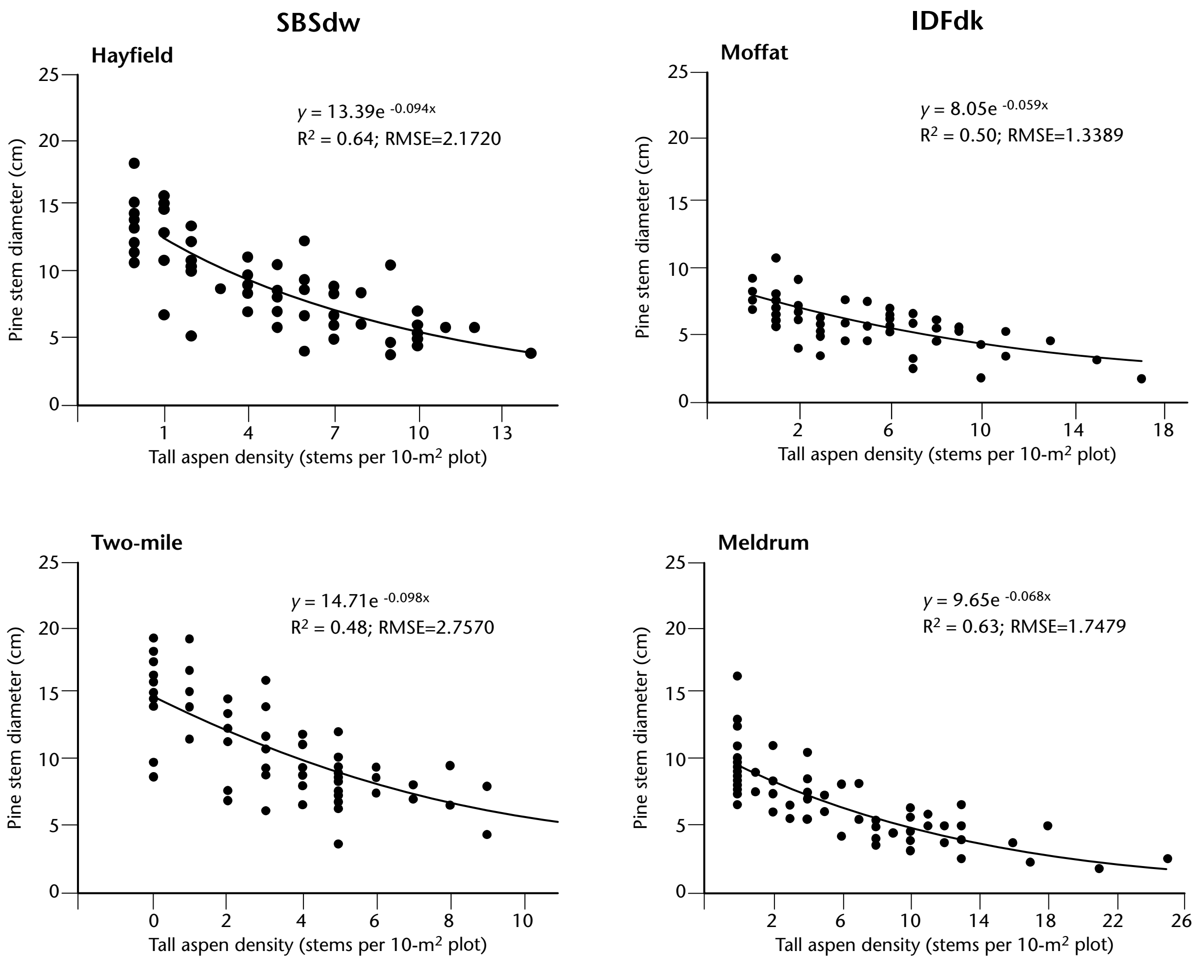


FIGURE 2 *Scatter plots and fitted non-linear regression lines showing the relationship between 1999 lodgepole pine stem diameter and tall aspen density (within a 10-m² plot around target pine) on the SBSdw (Hayfield and Two-mile) and IDFdk (Moffatt and Meldrum) sites.*

TABLE 9 *Regression equation[a] parameters and R^2 values for predicting lodgepole pine stem diameter, stem diameter increment, height, and leader length from tall aspen density[b] at three SBSdw sites*

	Hayfield						Two-mile						Oie Lake[c]					
	n[d]	***a***	***b***	R^2	**RMSE**[e]	***p*-value**	***n***	***a***	***b***	R^2	**RMSE**	***p*-value**	***n***	***a***	***b***	R^2	**RMSE**	***p*-value**
1992 stem diameter	51	6.15	–0.046	0.58	0.8406	< 0.0001	51	6.92	–0.040	0.40	1.1993	< 0.0001	50	4.22	–0.035	0.65	0.6363	< 0.0001
1992–1993 diameter increment	51	0.72	–0.062	0.32	0.2175	< 0.0001	51	1.08	–0.149	0.44	0.3154	< 0.0001	50	0.88	–0.039	0.50	0.2015	< 0.0001
1992 height	51	328.8	–0.013	0.12	51.4441	< 0.0001	51	360.8	–0.006	0.02	67.2867	< 0.0001	50	233.9	–0.018	0.42	39.4690	< 0.0001
1992 leader length	51	60.38	–0.023	0.19	11.7516	< 0.0001	51	63.70	–0.011	0.07	11.9373	< 0.0001	50	60.49	–0.021	0.54	8.8528	< 0.0001
1992–1999 diameter increment	44	6.28	–0.142	0.58	1.4946	< 0.0001	40	8.63	–0.165	0.68	1.6096	< 0.0001				n/a		
1999 stem diameter	61	13.39	–0.094	0.64	2.1720	< 0.0001	59	14.71	–0.098	0.48	2.7570	< 0.0001				n/a		
1999 leader length	61	62.80	–0.096	0.43	16.1648	< 0.0001	59	64.55	–0.101	0.28	20.8062	< 0.0001				n/a		

a General form of linear equation for all variables is: $y = ae^{bx} + \varepsilon$, where y is one of the pine growth variables, x is tall aspen density, ε is the residual error (assumed to be independent, with the same normal distribution for all plots), a and b are model parameters estimated by the (non–linear) least-squares method, and e is the base of the natural log (ln).

b Lodgepole pine 1992 stem diameter, 1992–1993 stem diameter increment, 1992 height, and 1992 leader length are predicted from tall aspen density in 1992. Lodgepole pine 1992–1999 stem diameter increment, 1999 stem diameter, and 1999 leader length are predicted from tall aspen density in 1999.

c The Oie Lake site was not included in the 1999 assessment.

d Sample sizes changed between 1992 and 1999 because additional plots were established in low aspen density classes and because some of the 1992 plots were lost due to pine mortality.

e RMSE is the root mean square error.

TABLE 10 *Regression equation[a] parameters and R^2 values for predicting lodgepole pine stem diameter, stem diameter increment, height, and leader length from tall aspen density[b] at three IDFdk sites*

	Moffatt						Meldrum						Raven[c]					
	n[d]	***a***	***b***	***R***^{2}	**RMSE**[e]	***p*-value**	***n***	***a***	***b***	***R***^{2}	**RMSE**	***p*-value**	***n***	***a***	***b***	***R***^{2}	**RMSE**	***p*-value**
1992 stem diameter	50	2.78	–0.035	0.43	0.4506	< 0.0001	49	4.00	–0.027	0.37	0.8257	< 0.0001	50	2.07	–0.018	0.41	0.3597	< 0.0001
1992–1993 diameter increment	50	0.79	–0.040	0.39	0.1533	< 0.0001	49	0.88	–0.042	0.47	0.1972	< 0.0001	50	0.54	–0.038	0.24	0.2317	< 0.0001
1992 height	50	160.5	–0.022	0.22	30.7799	< 0.0001	49	229.4	–0.015	0.17	50.7070	< 0.0001	50	108.2	–0.011	0.16	24.0187	< 0.0001
1992 leader length	50	41.35	–0.027	0.34	7.1255	< 0.0001	49	46.22	–0.020	0.33	8.5553	< 0.0001	50	29.98	–0.019	0.33	6.7975	< 0.0001
1992–1999 diameter increment	49	5.41	–0.067	0.52	0.9829	< 0.0001	49	5.97	–0.104	0.69	1.1792	< 0.0001				n/a		
1999 stem diameter	60	8.05	–0.059	0.50	1.3389	< 0.0001	59	9.65	–0.068	0.63	1.7479	< 0.0001				n/a		
1999 leader length	60	44.68	–0.035	0.11	15.1789	< 0.0001	59	46.57	–0.078	0.56	11.0860	< 0.0001				n/a		

a General form of linear equation for all variables is: $y = ae^{bx} + \varepsilon$, where y is one of the pine growth variables, x is tall aspen density, ε is the residual error (assumed to be independent, with the same normal distribution for all plots), a and b are model parameters estimated by the (non-linear) least-squares method, and e is the base of the natural log (ln).

b Lodgepole pine 1992 stem diameter, 1992–1993 stem diameter increment, 1992 height, and 1992 leader length are predicted from tall aspen density in 1992. Lodgepole pine 1992–1999 stem diameter increment, 1999 stem diameter, and 1999 leader length are predicted from tall aspen density in 1999.

c The Raven site was not included in the 1999 assessment.

d Sample sizes changed between 1992 and 1999 because additional plots were established in low aspen density classes and because some of the 1992 plots were lost due to pine mortality.

e RMSE is the root mean square error.

In 1992, tall aspen density explained more of the variation in pine stem diameter for SBSdw than IDFdk sites. The R^2 values for 1992–1999 diameter increment were similar for the two subzones, suggesting that aspen competition was equally important at the SBSdw and IDFdk sites during that period.

3.2.2 Predictive Ability of Competition Indices Spearman's rank correlation coefficients were calculated for pairings of lodgepole pine size (1992 stem diameter, 1992–1993 diameter increment, 1992 leader length) with various competition indices developed by other researchers. Based on rankings of the coefficients calculated for each site (Appendix 3; see Tables A3.7–A3.9), five indices were chosen for further investigation using non-linear regression analysis (Tables 11 and 12). The predictive ability of all five of the indices tended to be better for the SBSdw sites than for the IDFdk sites, and also tended to be better for 1992 stem diameter than for 1992–1993 diameter increment or 1992 leader length. In both subzones, the predictive ability of the indices was more variable among sites for leader length than for stem diameter.

For both SBSdw and IDFdk sites, the most successful competition indices were based on the ratio of aspen stem diameter to lodgepole pine stem diameter. The Navratil and MacIsaac CI (diameter of tallest aspen/target pine diameter) was the best predictor of 1992 pine stem diameter on SBSdw sites, accounting for 62–77% of the variation in size for that variable (Figure 3). The Lorimer CI [Σ (aspen diameter/target pine diameter)] was the best predictor of 1992 pine stem diameter on IDFdk sites, accounting for 51–59% of the variation (Figure 3). The Lorimer CI was also the best predictor of 1992 pine leader length, accounting for 9–64% of the variation in leader length at the SBSdw sites and 40–51% of the variation at the IDFdk sites. Of the indices that did not include a pine size variable, the Simard CI was most successful at predicting pine size. It explained 29–63% and 18–40% of the variation in 1992 pine stem diameter on SBSdw and IDFdk sites, respectively. For 1992 pine leader length, it explained 4–46% and 5–31% of the variation on SBSdw and IDFdk sites, respectively.

3.3 Lodgepole Pine Performance

Lodgepole pine performance was compared across tall aspen density classes using summary statistics and analysis of variance. Data were analyzed separately for each subzone and assessment year. To facilitate comparison between years, results are reported for only those four sites measured on all three assessment dates (1992, 1994 or 1997, 1999).

3.3.1 Lodgepole Pine Vigour In 1992, the majority of 8–12 year old target lodgepole pine at the SBSdw and IDFdk sites were assessed as having good or fair vigour in all tall aspen density classes (Figure 4, Table 13). This was attributed partly to the target pine selection criteria, which stipulated that pine of poor vigour should not be selected unless no better trees were available for a particular density class. Pine vigour was somewhat better at the IDFdk sites than at the SBSdw sites. In the IDFdk, 100% of pine were in good condition in neighbourhoods with up to 6000 tall aspen stems per hectare (six tall aspen stems in a 10-m^2 plot around the target pine). In the SBSdw, pine vigour declined slightly in neighbourhoods with more than 1000 tall aspen stems per hectare (one tall aspen stem in a 10-m^2 plot around the target pine).

In 1999, when lodgepole pine were 15–19 years old, vigour continued to be better at the IDFdk sites than at the SBSdw sites, although it had declined in

TABLE 11 *Regression equation[a,b] parameters and R^2 values for predicting stem diameter, stem diameter increment, and leader length for lodgepole pine growing among aspen at three SBSdw sites, using competition indices developed by other researchers[c]*

	Hayfield						Two-mile						Oie Lake					
	n	***a***	***b***	***R^2***	**RMSE[d]**	***p*-value**	***n***	***a***	***b***	***R^2***	**RMSE**	***p*-value**	***n***	***a***	***b***	***R^2***	**RMSE**	***p*-value**
Comeau, Braumandl, Xie CI (1993)																		
1992 stem diameter	50	6.17	–0. 012	0.63	0.7875	< 0.0001	51	6.73	–0.007	0.34	1.2390	< 0.0001	50	4.25	–0.010	0.66	0.6192	< 0.0001
1992–1993 diameter increment	50	0.75	–0.018	0.42	0.2010	< 0.0001	51	1.05	–0.030	0.39	0.3288	< 0.0001	50	0.88	–0.012	0.47	0.2078	< 0.0001
1992 leader length	50	62.39	–0.007	0.32	10.7981	< 0.0001	51	63.67	–0.002	0.09	11.8279	< 0.0001	50	60.68	–0.006	0.51	9.1292	< 0.0001
Navratil and MacIsaac CI (1993)																		
1992 stem diameter	50	6.71	–0.292	0.72	0.6850	< 0.0001	51	7.57	–0.289	0.62	0.9569	< 0.0001	50	4.56	–0.266	0.77	0.5135	< 0.0001
1992–1993 diameter increment	50	0.76	–0.351	0.31	0.2193	< 0.0001	51	1.10	–0.643	0.43	0.3191	< 0.0001	50	0.92	–0.277	0.44	0.2135	< 0.0001
1992 leader length	50	63.68	–0.153	0.24	0.2193	< 0.0001	51	66.27	–0.093	0.13	11.5672	< 0.0001	50	64.19	–0.170	0.60	8.2768	< 0.0001
Simard CI (1990)																		
1992 stem diameter	50	5.95	–0.006	0.49	0.9226	< 0.0001	51	6.55	–0.005	0.29	1.3043	< 0.0001	50	4.21	–0.009	0.63	0.6502	< 0.0001
1992–1993 diameter increment	50	0.70	–0.010	0.31	0.2198	< 0.0001	51	1.06	–0.025	0.43	0.3175	< 0.0001	50	0.86	–0.009	0.42	0.2159	< 0.0001
1992 leader length	50	55.52	–0.001	0.04	12.8141	< 0.0001	51	62.76	–0.001	0.06	12.0250	< 0.0001	50	59.84	–0.005	0.46	9.5500	< 0.0001

Continued

TABLE 11 *(Continued)*

	Hayfield						Two-mile						Oie Lake					
	n	***a***	***b***	***R^2***	**RMSE**	***p*-value**	***n***	***a***	***b***	***R^2***	**RMSE**	***p*-value**	***n***	***a***	***b***	***R^2***	**RMSE**	***p*-value**
Lorimer CI (1983)																		
1992 stem diameter	50	6.18	–0.040	0.71	0.7016	< 0.0001	51	7.02	–0.040	0.55	1.0328	< 0.0001	50	4.22	–0.026	0.74	0.5479	< 0.0001
1992–1993 diameter increment	50	0.73	–0.057	0.37	0.2090	< 0.0001	51	1.01	–0.122	0.38	0.3330	< 0.0001	50	0.88	–0.030	0.52	0.1977	< 0.0001
1992 leader length	50	61.06	–0.021	0.27	11.1355	< 0.0001	51	63.99	–0.011	0.09	11.7729	< 0.0001	50	60.60	–0.015	0.64	7.8139	< 0.0001
Daniels CI (1976)																		
1992 stem diameter	50	5.95	–2.583	0.62	0.8012	< 0.0001	51	6.82	–2.963	0.50	1.0996	< 0.0001	50	4.13	–2.096	0.70	0.5878	< 0.0001
1992–1993 diameter increment	50	0.69	–3.855	0.31	0.2198	< 0.0001	51	1.04	–12.292	0.42	0.3216	<0 .0001	50	0.85	–2.361	0.44	0.2126	< 0.0001
1992 leader length	50	56.96	–0.791	0.09	12.4378	< 0.0001	51	63.60	–0.821	0.09	11.7686	< 0.0001	50	59.28	–1.195	0.57	8.5157	< 0.0001

a General form of linear equation for all variables is: $y = ae^{bx} + \varepsilon$, where y is one of the pine growth variables, x is the competition index, ε is the residual error (assumed to be independent, with the same normal distribution for all plots), a and b are model parameters estimated by the (non-linear) least-squares method, and e is the base of the natural log (ln).

b Only aspen as tall or taller than the target pine were included in calculation of the competition indices.

c Equations for the competition indices are in provided in Section 2.3.5, Table 5.

d RMSE is the root mean square error.

TABLE 12 *Regression equation[a,b] parameters and R^2 values for predicting stem diameter, stem diameter increment, and leader length for lodgepole pine growing among aspen at three IDFdk sites, using competition indices developed by other researchers[c]*

	Moffat						Meldrum						Raven					
	n	***a***	***b***	R^2	**RMSE[d]**	***p*-value**	***n***	***a***	***b***	R^2	**RMSE**	***p*-value**	***n***	***a***	***b***	R^2	**RMSE**	***p*-value**
Comeau, Braumandl, Xie CI (1993)																		
1992 stem diameter	50	2.44	–0.010	0.38	0.4711	< 0.0001	49	3.63	–0.009	0.27	0.8901	< 0.0001	50	1.98	–0.016	0.33	0.3831	< 0.0001
1992–1993 diameter increment	50	0.72	–0.014	0.43	0.1483	< 0.0001	49	0.76	–0.013	0.25	0.237	< 0.0001	50	0.55	–0.043	0.28	0.2247	< 0.0001
1992 leader length	50	37.97	–0.008	0.39	6.8185	< 0.0001	49	42.48	–0.006	0.23	9.1491	<0.0001	50	28.98	–0.018	0.29	6.9792	< 0.0001
Navratil and MacIsaac CI (1993)																		
1992 stem diameter	50	3.22	–0.174	0.56	0.3940	< 0.0001	49	4.57	–0.283	0.47	0.7538	< 0.0001	50	2.27	–0.147	0.44	0.3504	< 0.0001
1992–1993 diameter increment	50	0.94	–0.202	0.50	0.1389	< 0.0001	49	0.88	–0.279	0.22	0.2400	< 0.0001	50	0.51	–0.178	0.10	0.2512	< 0.0001
1992 leader length	50	46.32	–0.202	0.50	0.1389	< 0.0001	49	48.49	–0.171	0.28	8.8298	< 0.0001	50	30.65	–0.120	0.21	7.3589	< 0.0001
Simard CI (1990)																		
1992 stem diameter	50	2.42	–0.004	0.18	0.5416	< 0.0001	49	3.67	–0.004	0.23	0.9128	< 0.0001	50	1.99	–0.005	0.40	0.3640	< 0.0001
1992–1993 diameter increment	50	0.69	–0.006	0.15	0.1822	< 0.0001	49	0.83	–0.008	0.38	0.2147	< 0.0001	50	0.58	–0.018	0.33	0.2166	< 0.0001
1992 leader length	50	34.54	–0.002	0.05	8.5406	< 0.0001	49	44.08	–0.003	0.31	8.6562	< 0.0001	50	28.83	–0.005	0.31	6.8599	< 0.0001

Continued

Table 12 (Continued)

	Moffat						Meldrum						Raven					
	n	***a***	***b***	R^2	**RMSE**	***p*-value**	***n***	***a***	***b***	R^2	**RMSE**	***p*-value**	***n***	***a***	***b***	R^2	**RMSE**	***p*-value**
Lorimer CI (1983)																		
1992 stem diameter	50	2.69	–0.017	0.59	0.3830	< 0.0001	49	4.04	–0.024	0.51	0.7267	< 0.0001	50	2.10	–0.012	0.55	0.3161	< 0.0001
1992–1993 diameter increment	50	0.76	–0.019	0.50	0.1389	< 0.0001	49	0.85	–0.032	0.48	0.1967	< 0.0001	50	0.56	–0.026	0.30	0.2220	< 0.0001
1992 leader length	50	40.40	–0.013	0.51	6.1149	< 0.0001	49	46.64	–0.017	0.47	7.5791	< 0.0001	50	30.17	–0.012	0.40	6.4135	< 0.0001
Daniels CI (1976)																		
1992 stem diameter	50	2.51	–0.844	0.43	0.4517	< 0.0001	49	3.90	–1.503	0.41	0.8013	< 0.0001	50	2.01	–0.558	0.50	0.3320	< 0.0001
1992–1993 diameter increment	50	0.68	–0.801	0.29	0.1661	< 0.0001	49	0.83	–2.152	0.40	0.2098	< 0.0001	50	0.58	–2.004	0.35	0.2145	< 0.0001
1992 leader length	50	36.71	–0.494	0.25	7.5893	< 0.0001	49	45.35	–1.042	0.47	7.6084	< 0.0001	50	29.13	–0.611	0.38	6.4980	< 0.0001

a General form of linear equation for all variables is: $y = ae^{bx} + \varepsilon$, where y is one of the pine growth variables, x is the competition index, ε is the residual error (assumed to be independent, with the same normal distribution for all plots), a and b are model parameters estimated by the (non-linear) least-squares method, and e is the base of the natural log (ln).

b Only aspen as tall or taller than the target pine were included in calculation of the competition indices.

c Equations for the competition indices are in provided in Section 2.3.5, Table 5.

d RMSE is the root mean square error.

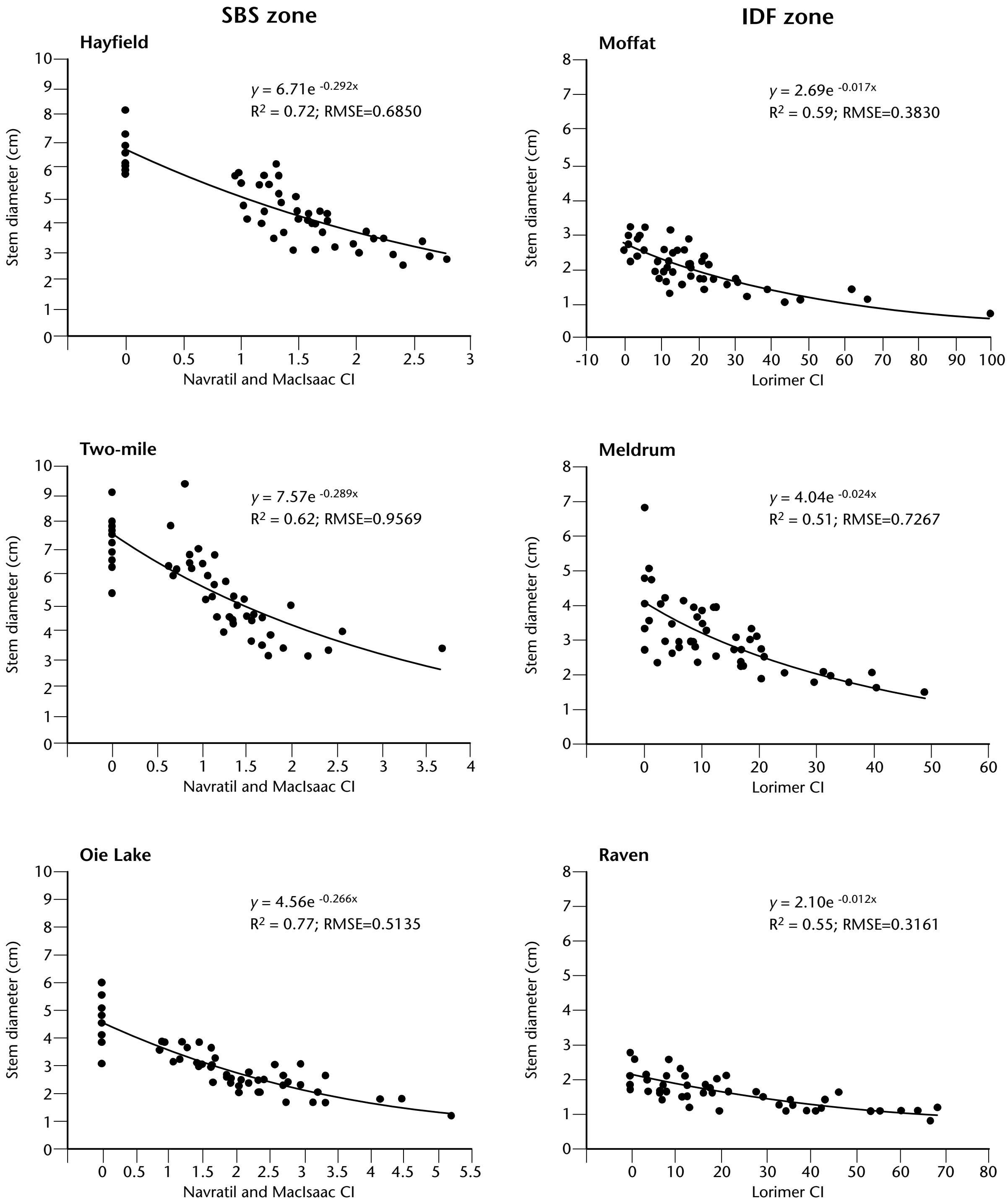


FIGURE 3 *Scatter plots and fitted non-linear regression lines showing the relationship between 1992 lodgepole pine stem diameter and the Navratil and MacIsaac CI on SBSdw sites (Hayfield, Two-mile, Oie Lake) and between 1992 lodgepole pine stem diameter and the Lorimer CI on IDFdk sites (Moffatt, Meldrum, Raven).*

TABLE 13 *Proportion of target lodgepole pine in good, fair, poor, and dead vigour classes at various ages at the SBSdw and IDFdk sites*[a]

	Tall aspen density[b]										
Stems per plot	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**≥ 10**
Stems per hectare	**0**	**1000**	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**≥ 10 000**
SBS											
1992											
(10- to 11-year-old pine)											
Good (%)	100.0	100.0	85.7	66.7	81.8	62.5	25.0	20.0	66.7	33.3	15.4
Fair (%)	0.0	0.0	14.3	33.3	18.2	37.5	75.0	60.0	33.3	66.7	73.1
Poor (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.0	0.0	0.0	11.5
Dead[c] (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1994											
(12- to 13-year-old pine)											
Good (%)	100.0	100.0	80.0	60.0	64.7	16.7	22.2	14.3	28.6	33.3	5.6
Fair (%)	0.0	0.0	20.0	40.0	29.4	66.7	77.8	71.4	57.1	66.7	72.2
Poor (%)	0.0	0.0	0.0	0.0	5.9	16.7	0.0	14.3	14.3	0.0	22.2
Dead (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1999											
(17- to 18-year-old pine)											
Good (%)	85.0	72.7	26.7	44.4	26.7	9.5	0.0	0.0	0.0	0.0	0.0
Fair (%)	15.0	18.2	46.7	11.1	40.0	28.6	23.1	57.1	0.0	16.7	0.0
Poor (%)	0.0	9.1	6.7	33.3	20.0	47.6	38.5	42.9	80.0	50.0	35.3
Dead (%)	0.0	0.0	20.0	11.1	13.3	14.3	30.5	0.0	20.0	33.3	64.7
IDF											
1992											
(8- to 12-year-old pine)											
Good (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	83.3	100.0	50.0	61.1
Fair (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.7	0.0	50.0	37.0
Poor (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9
Dead (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Continued

TABLE 13 *(Continued)*

	Tall aspen density[b]										
Stems per plot	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**≥ 10**
Stems per hectare	**0**	**1000**	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**≥ 10 000**
1997											
(13- to 17-year-old pine)											
Good (%)	78.6	73.3	45.5	40.0	27.3	16.7	16.7	0.0	14.3	75.0	39.4
Fair (%)	21.4	26.7	45.5	60.0	63.6	83.3	66.7	83.3	57.1	25.0	57.6
Poor (%)	0.0	0.0	9.1	0.0	9.1	0.0	16.7	16.7	28.6	0.0	3.0
Dead (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1999											
(15- to 19-year-old pine)											
Good (%)	73.7	80.0	33.3	12.5	25.0	20.0	11.1	12.5	0.0	0.0	0.0
Fair (%)	26.3	20.0	58.3	87.5	75.0	60.0	77.8	50.0	57.1	40.0	17.2
Poor (%)	0.0	0.0	8.3	0.0	0.0	20.0	11.1	12.5	42.9	60.0	58.6
Dead (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.0	0.0	0.0	20.7

a Means are based on data from the Hayfield and Two-mile sites in the SBSdw subzone, and the Moffatt and Meldrum sites in the IDFdk subzone.

b Pine were assigned to tall aspen density classes based on the number of tall aspen in 10-m^2 measurement plots at the time of assessment. For this reason, density classes did not necessarily include the same pine from year to year. Refer to Table 3 for the distribution of plots in tall aspen density classes in the various assessment years.

c Moribund and missing seedlings are classified as "dead."

both subzones. In the SBSdw, 100% of pine were in good or fair vigour in neighbourhoods with no tall aspen (0 stems per hectare), but vigour declined as tall aspen density increased (Figure 5). In neighbourhoods of up to 4000 tall aspen stems per hectare, more than 60% of pine were in good or fair condition. Above that density, more than one-half of the pine had died or were in the poor vigour class, and above 8000 tall aspen stems per hectare, almost all pine had died or were in poor condition. In contrast, vigour of pine in the IDFdk generally declined from good to fair as the stands aged, but the proportion of "poor" trees did not increase above 60% unless there were 9000 or more tall aspen stems per hectare in the neighbourhood (≥ 9 tall aspen stems in a 10-m^2 plot around the target pine).

In the same year (1999), most of the damage to lodgepole pine at both SBSdw and IDFdk sites was associated with physical "whipping" damage from aspen branches (e.g., forked and bent stems and leaders), and with competition for light (e.g., defoliation and curled leaders). Whipping damage to leaders and stems occurred in all tall aspen density classes except the 0 stems per hectare class, and although the trend was only weakly defined, the proportion of stems that were affected tended to increase with tall aspen density (Appendix 4; see Tables A4.1 and A4.2).

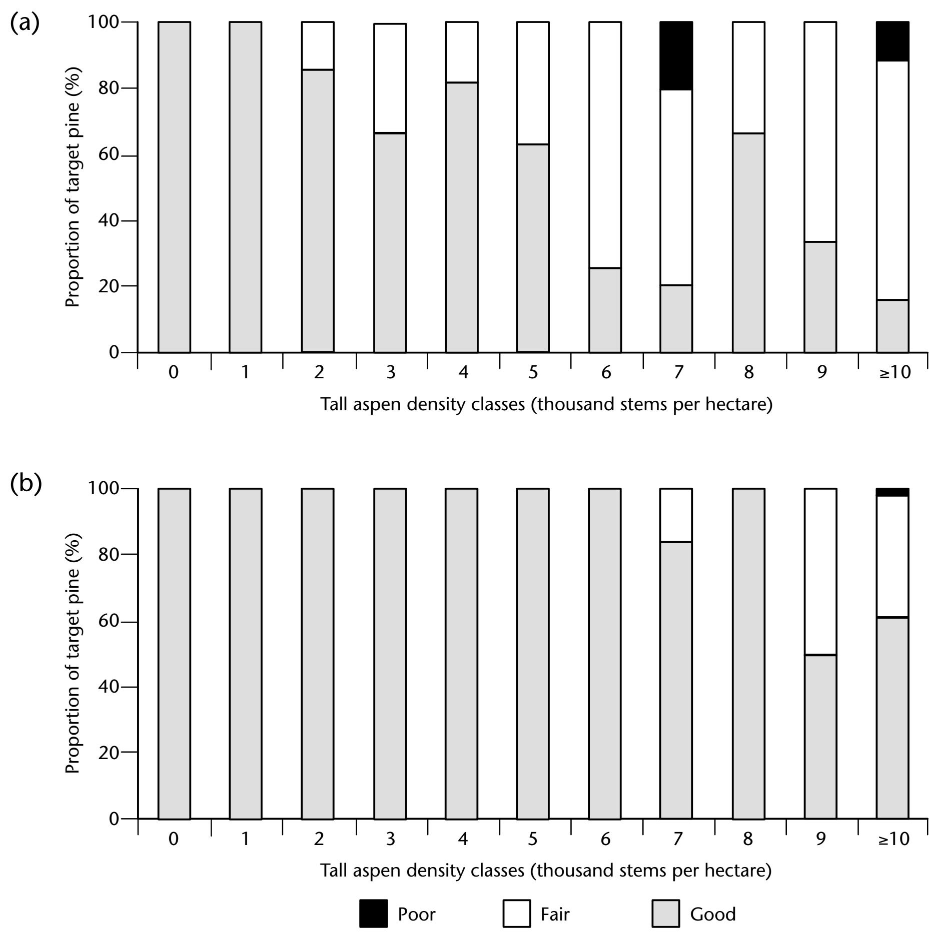


FIGURE 4 *Comparison of 1992 target lodgepole pine vigour among tall aspen density classes (based on tall aspen densities in 1992) at (a) SBSdw sites, and (b) IDFdk sites. There were no dead or moribund trees in the 1992 assessment.*

3.3.2 Lodgepole Pine Size In all measurement years, lodgepole pine diameter, height, and height–diameter ratio (HDR) varied significantly ($p \leq 0.05$; Tables 14 and 15) among some of the tall aspen density classes at both the SBSdw and IDFdk sites. The single exception was that no differences were evident among density classes for 1992 pine height in the IDFdk. The Bonferroni test was used to separate means where ANOVA found differences between density classes, but it was sometimes unable to identify differences where the p-value exceeded 0.01. This was the case for SBSdw pine height in 1992 ($p = 0.0372$), SBSdw HDR in 1994 ($p = 0.0268$), and IDFdk 1997–1999 diameter increment ($p = 0.0194$), and is possibly the result of small sample sizes in some of the density classes. It is still possible to identify trends, however. In general, as tall aspen density increased, pine stem diameter and height decreased and HDR increased. Differences in pine size became more apparent as stands aged, particularly at the SBSdw sites.

Lodgepole pine stem diameter was more strongly affected by increasing density of tall aspen than were height or HDR, and responses were somewhat different at the SBSdw and IDFdk sites. At the SBSdw sites, 10–11 year old (1992) pine stem diameter was significantly smaller in neighbourhoods where tall aspen density was ≥ 5000 stems per hectare than in neighbourhoods with no tall aspen (0 stems per hectare). By the time pine were 17–18 years old (1999), diameter was significantly smaller in neighbourhoods where tall aspen density was ≥ 2000 stems per hectare than in neighbourhoods with no tall aspen (Figure 6, Table 14). Among 8- to 12-year-old pine in the IDFdk (1992), those in neighbourhoods with ≥ 10 000 tall aspen stems per hectare had significantly smaller stem diameter than those in neighbourhoods with ≤ 1000 tall aspen stems per hectare. By the time IDFdk pine were 15–19 years old (1999), stem diameters tended to be significantly smaller where tall aspen density was ≥ 3000 stems per hectare than where no tall aspen were present, but differences were not consistently significant until tall aspen density was ≥ 5000 stems per hectare (i.e., differences were significant between the 0 and 3000 stems per hectare classes and the 0 and ≥ 5000 stems per hectare classes, but not between the 0 and 4000 stems per hectare classes) (Figure 6, Table 15). Pine diameter increments between 1992 and 1999 were also examined in relation to aspen density classes, and were significantly different in both subzones ($p \leq 0.05$; Table 16). At SBSdw sites, the 1992–1999 diameter increment was greater in the 0 tall aspen stems per hectare class than in any of the classes where tall aspen density was ≥ 2000 stems per hectare ($p < 0.0001$). At IDFdk sites, 1992–1999 stem diameter increment was greater in the 0 tall aspen stems per hectare class than in the ≥ 10 000 class (5.8 vs. 1.8 cm, $p = 0.0022$).

Pine had larger stem diameters at SBSdw sites than at IDFdk sites, and this trend was especially noticeable in low tall aspen density classes. In the SBSdw (Table 14), mean pine stem diameter in the 0 class was 6.9 cm when pine were 10–11 years old (1992) and 14.2 cm when they were 17–18 years old (1999). In the IDFdk (Table 15), mean pine stem diameter in the 0 class was 3.7 cm when pine were 8–12 years old (1992) and 9.3 cm when they were 15–19 years old (1999). At SBSdw sites, stem diameter declined sharply where tall aspen density exceeded 1000 stems per hectare, especially in 1999. At IDFdk sites, the decline was more gradual across the 11 density classes (Figure 6).

In 1992, the height of 8–12 year old lodgepole pine was fairly consistent across density classes at both the SBSdw and IDFdk sites (Figure 7). No significant differences across density classes for 1992 pine height were evident at

TABLE 14 *Mean[a] lodgepole pine stem diameter, height, and height-to-diameter ratio (HDR) in tall aspen density classes for SBSdw sites, in 1992, 1994, and 1999*

	Tall aspen density[b]											
Stems per plot (r = 1.78 m)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**≥ 10**	
Stems per hectare	**0**	**1000**	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**≥ 10 000**	***p*-value[c,d]**
1992 (10- to 11-year-old pine)												
Stem diameter (cm)	6.9 ± 0.4	6.2 ± 1.1	5.8 ± 0.5	5.6 ± 0.5	5.6 ± 0.5	4.9 ± 0.5	4.4 ± 0.4	4.1 ± 0.6	4.6 ± 0.7	4.3 ± 0.7	4.0 ± 0.4	< **0.0001**
	a	abc	ab	abc	ab	bc	bc	bc	bc	bc	c	
Height (cm)	348 ± 22	380 ± 64	335 ± 29	365 ± 30	338 ± 25	356 ± 28	292 ± 25	260 ± 33	323 ± 40	332 ± 40	302 ± 21	**0.0372†**
HDR	51 ± 2	61 ± 9	59 ± 3	65 ± 4a	61 ± 3	72 ± 3	66 ± 3	63 ± 4	68 ± 5	77 ± 5	77 ± 2	< **0.0001**
	d	abcd	bcd	abcd	bcd	ab	bc	abcd	abcd	ab	a	
1994 (12- to 13-year-old pine)												
Stem diameter (cm)	8.6 ± 0.3	8.5 ± 0.4	7.6 ± 0.4	6.3 ± 0.5	6.4 ± 0.4	6.2 ± 0.4	5.6 ± 0.5	5.1 ± 0.6	4.8 ± 0.6	5.4 ± 0.6c	4.8 ± 0.4	< **0.0001**
	a	a	ab	bc	bc	bc	bc	c	c	bc	c	
Height (cm)	478 ± 18	534 ± 23	493 ± 21	468 ± 25	449 ± 20	470 ± 23	387 ± 27	364 ± 30	387 ± 30	419 ± 33	382 ± 19	< **0.0001**
	ab	a	abc	abcd	abcd	abcd	bcd	d	bcd	abcd	d	
HDR	56 ± 3	64 ± 3	67 ± 3	77 ± 4	71 ± 3	76 ± 3	73 ± 4	71 ± 4	81 ± 4	80 ± 5	82 ± 3	**0.0268†**
1999 (17- to 18-year-old pine)												
Stem diameter (cm)	14.2 ± 0.7a	13.8 ± 0.9	10.9 ± 0.8	10.3 ± 1.0	9.1 ± 0.8	7.9 ± 0.7	8.4 ± 0.9	7.2 ± 1.0	7.6 ± 1.3	6.0 ± 1.1	6.0 ± 0.9	< **0.0001**
	a	0.9a	bc	bcd	cde	cde	cde	cde	cde	de	e	
Height (cm)	772 ± 28	818 ± 37	728 ± 34	729 ± 44	661 ± 34	609 ± 28	578 ± 41	565 ± 47	584 ± 62	515 ± 51	498 ± 39	< **0.0001**
	a	a	ab	abc	abcd	bcd	bcd	bcd	abcd	cd	d	
HDR	56 ± 4	61 ± 5	70 ± 5	73 ± 6	73 ± 5	77 ± 4	74 ± 6	81 ± 6	80 ± 8	91 ± 7	89 ± 6	< **0.0001**
	c	bc	abc	abc	abc	ab	abc	ab	abc	a	a	

a Values are presented in the form of "mean ± 1 standard error."

b Pine were assigned to tall aspen density classes based on the number of tall aspen in 10-m^2 measurement plots at the time of assessment. For this reason, density classes did not necessarily include the same pine from year to year. Refer to Table 3 for the distribution of plots in tall aspen density classes in the various assessment years.

c Values in **bold type** are significant at $p \leq 0.05$, according to ANOVA. Means having different letters are significantly different within the given year. Mean separation was done with the Bonferroni test.

d † Indicates the Bonferroni test found no differences between classes, even though $p \leq 0.05$ according to ANOVA.

TABLE 15 *Mean[a] lodgepole pine stem diameter, height, and height-to-diameter ratio (HDR) in tall aspen density classes for IDFdk sites, in 1992, 1997, and 1999*

	Tall aspen density[b]											
Stems per plot (r = 1.78 m)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**≥ 10**	
Stems per hectare	**0**	**1000**	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**≥ 10 000**	***p*-value[c,d]**
1992 (8- to 12-year-old pine)												
Stem diameter (cm)	3.7 ± 0.5	3.6 ± 0.6	3.0 ± 0.6	3.2 ± 0.6	3.0 ± 0.5	2.9 ± 0.9	2.4 ± 0.5	2.3 ± 0.5	2.4 ± 0.6	2.3 ± 0.7	2.2 ± 0.5	< **0.0001**
	a	a	ab	ab	ab	ab	ab	ab	ab	ab	b	
Height (cm)	191 ± 36	182 ± 37	176 ± 38	202 ± 40	191 ± 36	170 ± 55	176 ± 35	150 ± 36	163 ± 37	144 ± 44	154 ± 31	0.3603
HDR	54 ± 4	50 ± 4	59 ± 4	63 ± 5	63 ± 4	56 ± 9	73 ± 3	65 ± 4	68 ± 4	63 ± 6	70 ± 1	< **0.0001**
	b	b	ab	ab	ab	ab	a	ab	ab	ab	a	
1997 (13- to 17-year-old pine)												
Stem diameter (cm)	8.0 ± 0.6	7.5 ± 0.6	6.3 ± 0.6	5.2 ± 0.8	5.6 ± 0.6	6.2 ± 0.7	5.8 ± 0.7	4.9 ± 0.7	5.1 ± 0.7	4.9 ± 0.8	3.8 ± 0.5	< **0.0001**
	a	ab	abc	bcd	bc	abc	abcd	cd	cd	bcd	d	
Height (cm)	429 ± 32	435 ± 31	365 ± 33	389 ± 41	372 ± 33	381 ± 39	362 ± 38	355 ± 39	315 ± 37	363 ± 44	272 ± 28	< **0.0001**
	a	a	ab	abc	ab	abc	abc	abc	bc	abc	c	
HDR	55 ± 3	59 ± 3	60 ± 3	77 ± 5	68 ± 3	65 ± 5	63 ± 5	75 ± 5	62 ± 4	76 ± 6	73 ± 2	< **0.0001**
	c	bc	abc	ab	abc	abc	abc	ab	abc	abc	a	
1999 (15- to 19-year-old pine)												
Stem diameter (cm)	9.3 ± 0.5	8.1 ± 0.6	7.6 ± 0.6	5.8 ± 0.7	7.1 ± 0.7	6.4 ± 0.8	6.5 ± 0.6	5.6 ± 0.7	4.9 ± 0.7	5.2 ± 0.8	3.9 ± 0.5	< **0.0001**
	a	ab	ab	bcd	abc	bcd	bc	bcd	cd	bcd	d	
Height (cm)	501 ± 30	542 ± 35	449 ± 33	442 ± 36	434 ± 36	433 ± 42	456 ± 35	388 ± 36	353 ± 38	410 ± 42	290 ± 29	< **0.0001**
	a	a	ab	ab	ab	ab	ab	bc	bc	abc	c	
HDR	55 ± 3	69 ± 4	60 ± 3	78 ± 4	64 ± 4	69 ± 5	70 ± 4	71 ± 4	73 ± 5	81 ± 5	76 ± 2	< **0.0001**
	c	abc	bc	ab	abc	abc	abc	abc	abc	ab	a	

a Values are presented in the form of "mean ± 1 standard error."

b Pine were assigned to tall aspen density classes based on the number of tall aspen in 10-m² measurement plots at the time of assessment. For this reason, density classes did not necessarily include the same pine from year to year. Refer to Table 3 for the distribution of plots in tall aspen density classes in the various assessment years.

c Values in **bold type** are significant at $p \leq 0.05$, according to ANOVA. Means having different letters are significantly different within the given year. Mean separation was done with the Bonferroni test.

d † Indicates the Bonferroni test found no differences between classes, even though $p \leq 0.05$ according to ANOVA.

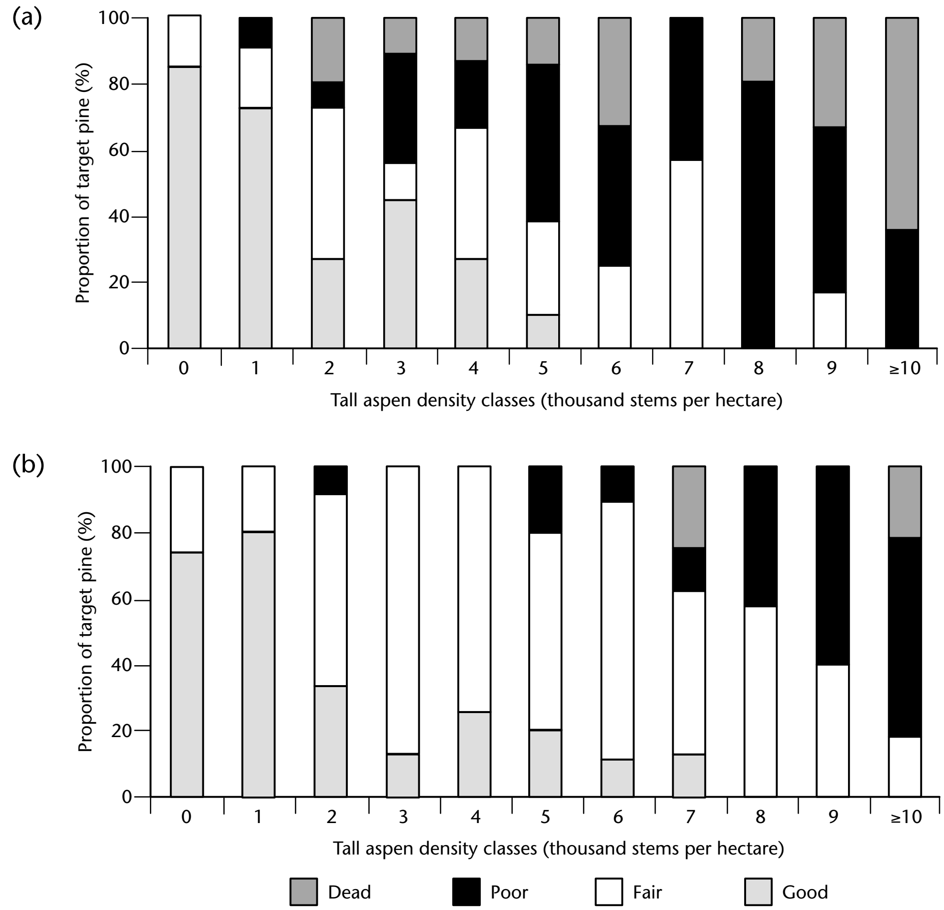


FIGURE 5 *Comparison of 1999 target lodgepole pine vigour among tall aspen density classes (based on tall aspen densities in 1999) at (a) SBSdw sites and (b) IDFdk sites. Moribund and missing seedlings are classified as "dead."*

the IDFdk sites, and although ANOVA revealed significant differences for SBSdw sites ($p = 0.0372$), the Bonferroni test was unable to separate the means. Visual examination of height data does not show a strong trend across tall aspen density classes in 1992. By 1999, when pine were 15–19 years old, trends were somewhat different in the two subzones. In the SBSdw, pine were showing a trend of decreasing height with increasing aspen density by age 17–18 years (Table 14). In 1999, pine were significantly shorter where tall aspen density was ≥ 5000 stems per hectare than where tall aspen density was ≤ 1000 stems per hectare. Pine associated with the 8000 stems per hectare class did not follow this trend (i.e., these pine were not significantly shorter than pine associated with the 0 and 1000 stems per hectare classes) because of relatively high variability within the class (s.e. = 62 cm).

Among 15- to 19-year-old pine (1999) at the IDFdk sites, height tended to decline significantly only where tall aspen density was ≥ 7000 stems per hectare, but the trend was somewhat inconsistent (Figure 7, Table 15). At both the SBSdw and IDFdk sites, the 1992–1999 pine height increment differed significantly across tall aspen density classes and gradually declined between the 0 and 10 000 stems per hectare classes ($p \leq 0.05$; Table 16). The

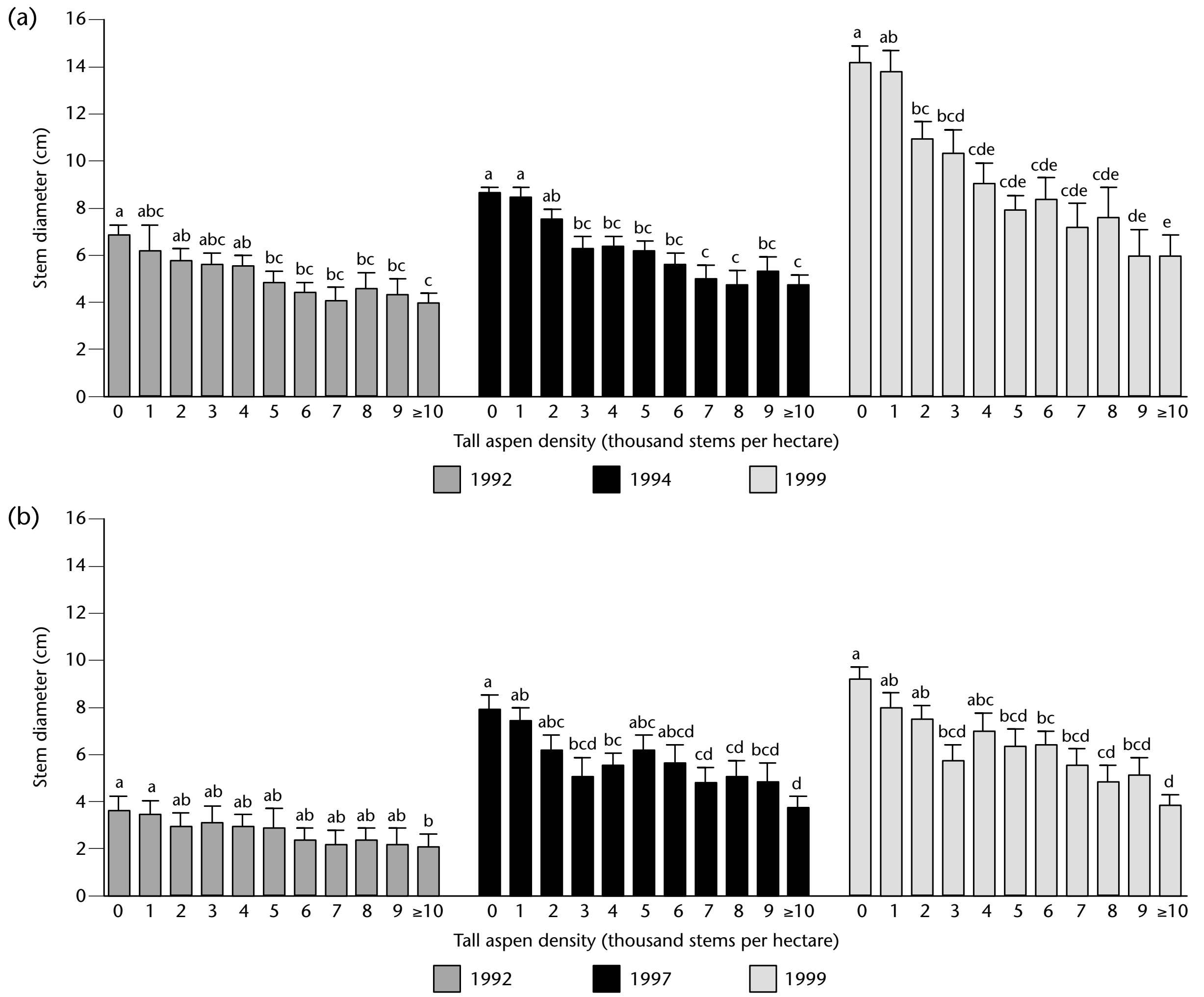


FIGURE 6 *Mean lodgepole pine stem diameter (± 1 standard error) among tall aspen density classes at (a) SBSdw sites in 1992, 1994, and 1999, and (b) IDFdk sites in 1992, 1997, and 1999. Density classes are based on aspen as tall or taller than the target pine in the measurement year. Means having the same letter within a single year are not significantly different from one another according to the Bonferroni test (p > 0.05).*

1992–1999 height increments in the ≥ 10 000 stems per hectare class at the SBSdw and IDFdk sites were 53 and 54% less, respectively, than height increments in the 0 stems per hectare class (Figure 8). At SBSdw sites, pine in neighbourhoods with no tall aspen increased in height by a significantly greater amount (432 cm) between 1992 and 1999 than pine in the ≥ 8000 stems per hectare class (203–241 cm, $p < 0.0001$). Between 1992 and 1999, pine in IDFdk neighbourhoods with ≤ 1000 tall aspen stems per hectare increased significantly more in height than those in neighbourhoods with ≥ 7000 stems per hectare (314–370 cm vs. 145–232 cm, $p < 0.0001$). Lodgepole pine were taller at the SBSdw than the IDFdk sites in all measurement years. In 1992, when pine were 8–12 years old, mean height ranged from 260 to 380 cm at the SBSdw sites, compared with 144 to 202 cm at the IDFdk sites. By 1999, mean height ranged from 498 to 818 cm at the SBSdw sites and from 290 to 542 cm at the IDFdk sites. Although differences in pine height between the 0 and 1000 stems per hectare density classes were not statistically

TABLE 16 *Mean[a] lodgepole pine growth increments in tall aspen density classes, from 1992 to 1999, for SBSdw and IDFdk sites*

	Tall aspen density[b]											
Stems per plot (r = 1.78 m)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**≥ 10**	
Stems per hectare	**0**	**1000**	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**≥ 10 000**	***p*-value[c,d]**
SBSdw												
Height increment (cm)												
1992–1999	432 ± 22	375 ± 54	349 ± 47	399 ± 42	378 ± 31	249 ± 24	280 ± 38	279 ± 47	241 ± 47	225 ± 38	203 ± 30	< **0.0001**
	a	abc	abc	ab	ab	bc	abc	abc	bc	bc	c	
1994–1999	298 ± 16	292 ± 22	233 ± 20	226 ± 26	214 ± 20	170 ± 17	158 ± 24	173 ± 28	33 ± 37	134 ± 30	124 ± 23	< **0.0001**
	a	ab	abc	abcd	abcd	cd	cd	bcd	cd	cd	d	
Diameter increment (cm)												
1992–1999	7.6 ± 0.7	6.5 ± 1.1	4.5 ± 1.0	4.6 ± 0.9	4.4 ± 0.8	2.7 ± 0.7	3.1 ± 0.9	2.7 ± 1.0	2.7 ± 1.0	2.4 ± 0.9	2.1 ± 0.8	< **0.0001**
	a	ab	bc	bc	bc	c	bc	bc	bc	bc	c	
1994–1999	5.6 ± 0.4	5.0 ± 0.5	3.7 ± 0.5	3.1 ± 0.5	3.0 ± 0.5	2.0 ± 0.4	2.8 ± 0.5	2.1 ± 0.6	1.6 ± 0.7	1.5 ± 0.6	1.1 ± 0.5	< **0.0001**
	a	ab	bc	bcd	cd	d	cd	cd	cd	cd	d	
IDFdk												
Height increment (cm)												
1992–1999	314 ± 18	370 ± 31	314 ± 26	274 ± 25	286 ± 28	261 ± 31	272 ± 22	223 ± 23	216 ± 24	232 ± 28	145 ± 15	< **0.0001**
	ab	a	abc	abc	abc	abc	abc	cd	cd	bcd	d	
1997–1999	81 ± 7	88 ± 9	73 ± 8	80 ± 10	72 ± 10	63 ± 12	69 ± 9	50 ± 10	50 ± 10	53 ± 12	33 ± 7b	**0.0153**
	a	ab	ab	ab	ab	ab	ab	ab	ab	ab	b	
Diameter increment (cm)												
1992–1999	5.8 ± 0.3	5.0 ± 0.6	5.2 ± 0.5	3.5 ± 0.5	4.2 ± 0.5	3.8 ± 0.6	3.9 ± 0.4	3.1 ± 0.4	2.9 ± 0.5	2.6 ± 0.5	1.8 ± 0.3	**0.0022**
	a	ab	a	ab	ab	ab	ab	ab	ab	ab	b	
1997–1999	1.5 ± 0.1	0.9 ± 0.2	1.2 ± 0.2	0.8 ± 0.2	1.2 ± 0.2	0.8 ± 0.2	0.8 ± 0.2	0.5 ± 0.2	0.5 ± 0.2	0.2 ± 0.2	0.3 ± 0.1	**0.0194†**

a Values are presented in the form of "mean ± 1 standard error."

b Pine were assigned to tall aspen density classes based on the number of tall aspen in 10-m² measurement plots at the time of assessment. For this reason, density classes did not necessarily include the same pine from year to year. Refer to table 3 for the distribution of plots in tall aspen density classes in the various assessment years.

c Values in **bold type** are significant at $p \leq 0.05$, according to ANOVA. Means having different letters are significantly different within the given period. Mean separation was done with the Bonferroni test.

d † Indicates the Bonferroni test found no differences between classes, even though $p \leq 0.05$ according to ANOVA.

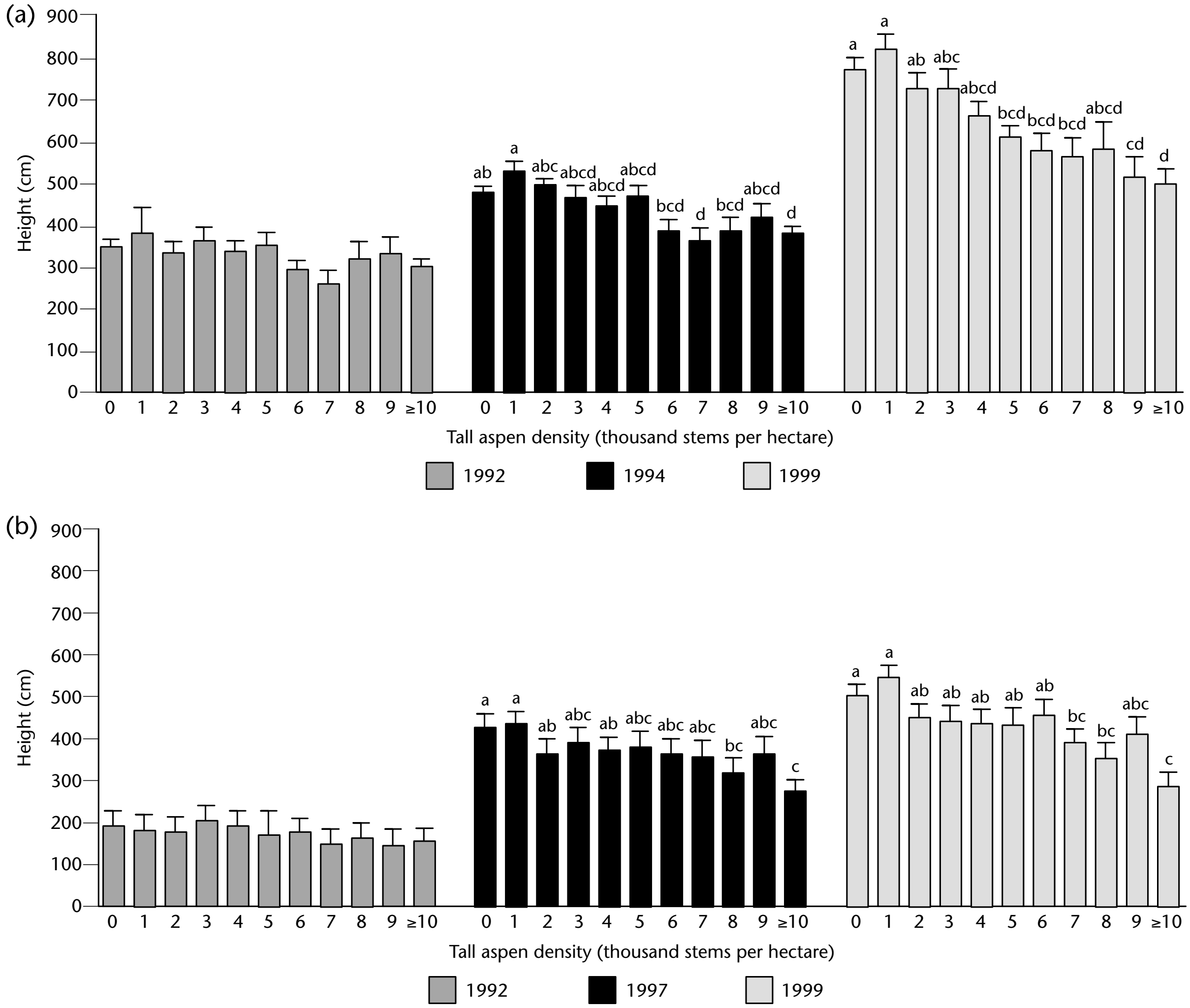


FIGURE 7 *Mean lodgepole pine height (± 1 standard error) among tall aspen density classes at (a) SBSdw sites in 1992, 1994, and 1999, and (b) IDFdk sites in 1992, 1997, and 1999. Density classes are based on aspen as tall or taller than the target pine in the measurement year. Means having the same letter within a single year are not significantly different from one another according to the Bonferroni test (p > 0.05). Means for the SBSdw in 1992 were significantly different according to ANOVA (p = 0.0372), but could not be separated with the Bonferroni test. In the IDFdk, means were not significantly different in 1992.*

significant in either subzone, visual observation of trends suggests that pine growing in neighbourhoods with 1000 stems per hectare were responding to the slight reduction in light availability by increasing in height.

At SBSdw sites, lodgepole pine HDR differed significantly between tall aspen density classes ($p \leq 0.05$), although significant mean separation was found only between the 0 versus 9000 and 0 versus ≥ 10 000 stems per hectare classes (Table 14). This relationship appeared to hold for all measurement years, although the Bonferroni test could not separate means for 1994 in the SBSdw subzone. Height-to-diameter ratio integrates height and diameter, and is a useful variable for identifying the severity of light competition effects on pine growth. At both the SBSdw and IDFdk sites, HDR increased with tall aspen density until height growth was also compromised by aspen competition, after which the rate of HDR increase slowed (Figure 9). Large increases in HDR in lower aspen density classes in the IDFdk suggest pine were increasing in height, but not at the expense of diameter growth. Pine HDR in the SBSdw showed a similar trend in 1992, but by 1999, increases in competition effects had caused diameter growth to also slow, mitigating the effect (Figure 9).

3.4 Neighbourhood Vegetation

3.4.1 Aspen Based on time since disturbance, aspen in this study were estimated to be 9- to 15-years-old in 1992 (Table 2). Over the 7-year measurement period, tall aspen in the various density classes increased in height at rates of 56–92 cm per year at the SBSdw sites and 35–57 cm per year at the IDFdk sites. No significant differences in height were evident across density classes for either subzone in 1992 or 1999 ($p > 0.05$). In the SBSdw, tall aspen averaged 523 cm in height when stands were 14–15 years old (1992) and 1024 cm when stands were 21–22 years old (1999). In the IDFdk, tall aspen averaged 305 cm in height when stands were 11–12 years old (1992) and 617 cm when stands were 18–19 years old (1999) (Table 17).

At SBSdw sites, aspen in all density classes were increasing in height more quickly than target pine (56–92 cm per year for aspen vs. 29–62 cm per year for pine). At IDFdk sites, aspen in density classes of 4000 or more stems per hectare were increasing in height more quickly than pine (36–57 cm per year for aspen vs. 21–39 cm per year for pine), whereas in lower density neighbourhoods, aspen and pine were growing at approximately the same rate (35–51 cm per year for aspen vs. 39–53 cm per year for pine). In both subzones, pine would obviously continue to be overtopped by aspen for some time (Figure 10).

At SBSdw sites, diameter of tall aspen averaged 5.1 cm in 1992, with no significant differences between density classes ($p = 0.8393$; Table 17). By 1999, aspen diameters were decreasing as tall aspen density increased; diameters

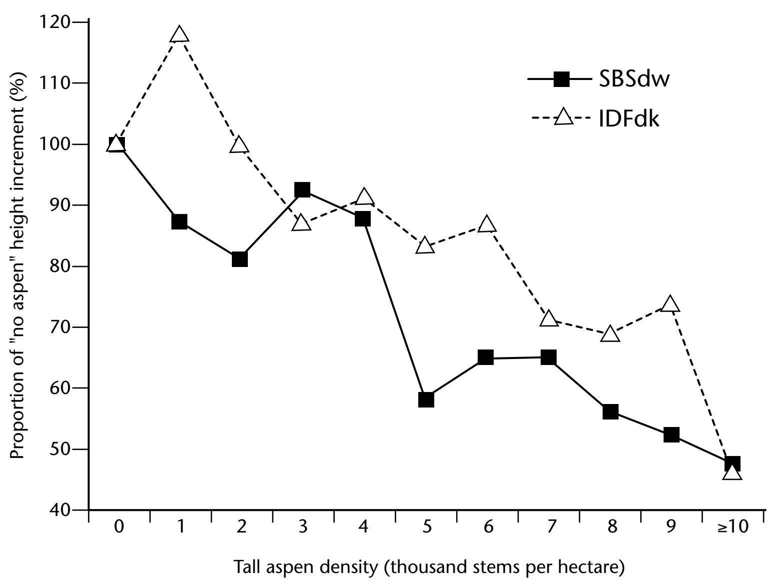


FIGURE 8 *Trends in 1992–1999 lodgepole pine height increment across tall aspen density classes at SBSdw and IDFdk sites. Values are expressed as a percentage of the 1992–1999 height increment in the 0 stems per hectare class for each subzone.*

TABLE 17 *Mean[a] tall aspen height, diameter, and basal area at SBSdw and IDFdk sites in 1992 and 1999*

	Tall aspen density[b]											
Stems per plot (r = 1.78 m)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**≥ 10**	
Stems per hectare	**0**	**1000**	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**≥ 10 000**	***p*-value[c]**
SBSdw												
Height (cm)												
1992	n/a	507 ± 127	480 ± 53	579 ± 50	497 ± 46	554 ± 46	520 ± 44	498 ± 47	544 ± 54	526 ± 48	525 ± 42	0.7081
1999	n/a	1090 ± 98	1124 ± 84	1093 ± 85	974 ± 79	1066 ± 76	1001 ± 78	959 ± 79	1064 ± 82	952 ± 78	916 ± 75	0.0541
Diameter (cm)												
1992	n/a	5.5 ± 1.6	5.3 ± 0.6	5.6 ± 0.5	5.2 ± 0.5	5.3 ± 0.5	5.0 ± 0.5	5.2 ± 0.5	5.0 ± 0.7	4.6 ± 0.5	4.5 ± 0.4	0.8393
1999	n/a	10.9 ± 0.8	10.6 ± 0.6	9.8 ± 0.6	8.9 ± 0.5	9.6 ± 0.4	9.2 ± 0.5	7.5 ± 0.5	8.3 ± 0.6	7.7 ± 0.5	7.2 ± 0.4	**0.0071**
		ab	a	ab	ab	ab	ab	ab	ab	ab	b	
Basal area (m^2/ha)												
1992	n/a	1.1 ± 5.6	4.9 ± 3.0	7.8 ± 3.1	8.8 ± 2.8	12.8 ± 3.0	12.7 ± 2.8	17.3 ± 3.3	16.0 ± 4.1	16.1 ± 3.7	23.9 ± 2.6	0.0132
		ab	b	ab	ab	ab	ab	ab	ab	ab	a	
1999	n/a	9.5 ± 5.8	18.6 ± 5.6	23.0 ± 6.6	26.5 ± 5.6	39.6 ± 5.4	42.7 ± 6.1	34.0 ± 6.5	46.0 ± 7.4	46.0 ± 6.7	57.1 ± 6.1	**0.0078**
		b	ab	ab	ab	ab	ab	ab	ab	ab	a	
IDFdk												
Height (cm)												
1992	n/a	272 ± 51	283 ± 41	304 ± 39	353 ± 26	241 ± 51	301 ± 21	290 ± 21	319 ± 21	364 ± 29	325 ± 12	0.1079
1999	n/a	630 ± 55	572 ± 40	594 ± 40	596 ± 36	642 ± 39	651 ± 32	624 ± 32	571 ± 32	653 ± 33	624 ± 25	0.2886
Diameter (cm)												
1992	n/a	3.2 ± 0.6	3.2 ± 0.5	3.4 ± 0.4	4.3 ± 0.3	2.6 ± 0.6	3.2 ± 0.2	3.0 ± 0.2	3.2 ± 0.2	3.3 ± 0.3	3.1 ± 0.1	**0.0051**
		ab	ab	ab	a	ab	b	b	b	ab	b	
1999	n/a	6.4 ± 0.7	5.6 ± 0.5	5.9 ± 0.5	5.9 ± 0.5	6.2 ± 0.5	5.9 ± 0.4	5.5 ± 0.4	5.1 ± 0.4	5.2 ± 0.4	5.1 ± 0.4	0.5658
Basal area (m^2/ha)												
1992	n/a	0.9 ± 2.1	2.0 ± 2.3	3.2 ± 2.7	7.0 ± 1.9	3.4 ± 4.6	5.3 ± 1.7	6.0 ± 1.9	7.2 ± 2.1	8.8 ± 3.3	13.5 ± 0.6	< **0.0001**
		b	b	b	ab	ab	b	b	ab	ab	a	
1999	n/a	3.1 ± 2.4	5.4 ± 2.2	8.2 ± 2.6	12.3 ± 2.6	16.3 ± 3.3	18.2 ± 2.5	18.3 ± 2.6	17.6 ± 2.8	21.0 ± 3.3	29.0 ± 1.5	< **0.0001**
		d	cd	bcd	bcd	bc	b	b	b	ab	a	

a Values are presented in the form of "mean ± 1 standard error."

b Tall aspen density refers to the density of aspen as tall or taller than the target lodgepole pine in the measurement year.

c Values in **bold type** are significant at $p \leq 0.05$, according to ANOVA. Means having different letters are significantly different within the given year. Mean separation was done with the Bonferroni test.

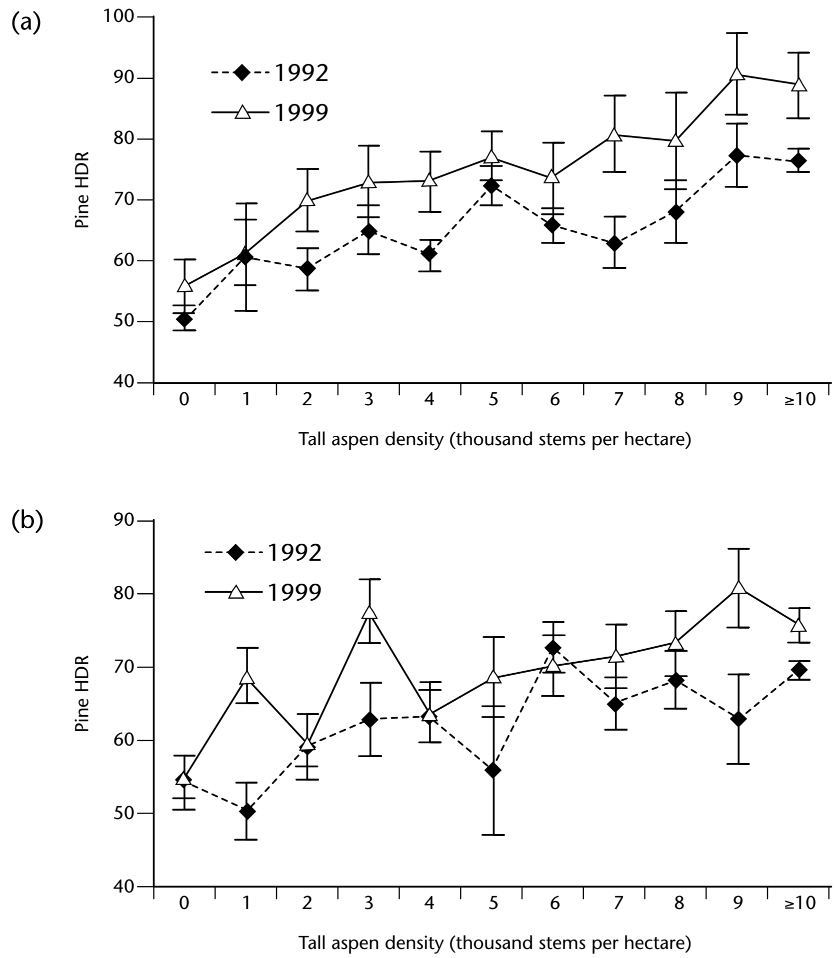


FIGURE 9 *Comparison of mean lodgepole pine height-to-diameter ratio (HDR) among tall aspen density classes at (a) SBSdw sites and (b) IDFdk sites in 1992 and 1999. Density classes are based on aspen as tall or taller than the target pine in the measurement year. Error bars represent 1 standard error.*

associated with the 1000 stems per hectare class were significantly larger than those associated with the ≥ 10 000 class (10.9 versus 7.2 cm, $p = 0.0071$). At IDFdk sites, aspen stem diameters varied significantly in 1992, but no obvious trend was evident. By 1999, aspen diameters were no longer significantly different across tall aspen density classes, although a trend of decreasing diameter was evident where tall aspen density exceeded 7000 stems per hectare. Average 1999 aspen diameter across all density classes at IDFdk sites was 5.7 cm.

Aspen basal area was consistently higher at SBSdw sites than at IDFdk sites regardless of whether tall aspen or all aspen were considered, and this trend became stronger with time (Table 17, Table 18). In both subzones, tall aspen basal area more than doubled in most tall aspen density classes between 1992 and 1999, and tended to be at least twice as high in the SBSdw as the IDFdk (Figure 11).

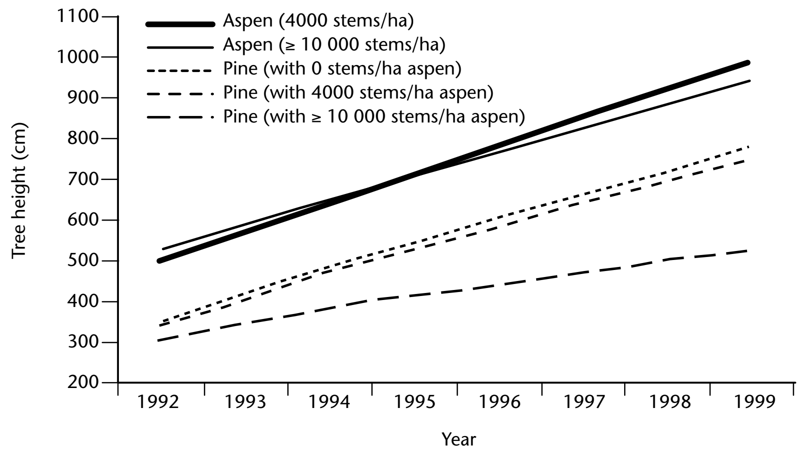
3.4.2 Light Availability under the Aspen Canopy Percent full sunlight under clear sky conditions (as measured in 1992; see Section 2.3.4) differed across density classes, at both the SBSdw and IDFdk sites ($p \leq 0.05$)

TABLE 18 *Mean[a] total[b] aspen density and basal area in tall aspen density classes at SBSdw and IDFdk sites in 1992 and 1999*

	Tall aspen density[c]											
Stems per plot (r = 1.78 m)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**≥ 10**	
Stems per hectare	**0**	**1000**	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**≥ 10 000**	***p*-value[d]**
SBSdw												
Density (stems per hectare)												
1992	889 ± 1930	9703 ± 5249	8988 ± 2446	12 000 ± 2500	7476 ± 2187	9809 ± 2381	9655 ± 2094	10 600 ± 2765	10 036 ± 25	11 763 ± 3200	19 615 ± 1838	**0.0216**
	b	ab	ab	ab	ab	ab	ab	ab	ab	ab	a	
1999	1500 ± 636	3373 ± 779	4215 ± 733	5630 ± 924	5165 ± 733	6317 ± 657	7701 ± 848	7977 ± 941	10 750 ± 1178	12 161 ± 997	15 008 ± 835	**0.0017**
	c	bc	bc	bc	bc	bc	abc	abc	abc	ab	a	
Basal area (m^2/ha)												
1992	1.8 ± 3.5	5.8 ± 5.7	8.0 ± 3.4	12.0 ± 3.4	9.6 ± 3.2	14.6 ± 3.3	14.1 ± 3.1	18.3 ± 3.6	15.7 ± 4.2	17.4 ± 3.9	25.9 ± 3.0	**0.0004**
	c	abc	bc	bc	bc	abc	bc	ab	abc	abc	a	
1999	1.6 ± 5.4	12.3 ± 5.5	21.1 ± 5.4	27.5 ± 6.4	27.8 ± 5.4	41.9 ± 5.2	44.5 ± 5.8	34.4 ± 6.2	48.4 ± 7.1	49.5 ± 6.4	59.9 ± 5.9	**0.0013**
	c	bc	bc	abc	abc	ab	ab	abc	ab	ab	a	
IDFdk												
Density (stems per hectare)												
1992	0 ± 3371	4315 ± 3480	6750 ± 3660	10 859 ± 3948	11 115 ± 3371	12 577 ± 5753	12 797 ± 3260	11 885 ± 3371	13 146 ± 3493	13 000 ± 4457	21 756 ± 2720	< **0.0001**
	c	bc	bc	bc	b	abc	b	b	b	bc	a	
1999	2990 ± 1558	4487 ± 1725	5271 ± 1663	8781 ± 1801	6422 ± 1795	9863 ± 2014	10 840 ± 1759	10 328 ± 1795	14 527 ± 1849	12 863 ± 2014	15 438 ± 1498	< **0.0001**
	f	ef	def	bcde	cdef	bcde	bc	bcd	ab	abc	a	
Basal area (m^2/ha)												
1992	0.6 ± 2.3	1.3 ± 2.0	3.0 ± 2.3	4.7 ± 2.6	9.4 ± 1.9	4.1 ± 4.5	6.5 ± 1.7	6.5 ± 1.9	8.1 ± 2.0	9.3 ± 3.2	14.7 ± 0.6	< **0.0001**
	b	b	b	b	ab	ab	b	b	ab	ab	a	
1999	3.3 ± 1.6	5.9 ± 2.2	7.5 ± 2.1	12.1 ± 2.4	13.7 ± 2.4	19.1 ± 3.1	21.1 ± 2.3	20.3 ± 2.4	20.9 ± 2.6	23.0 ± 3.1	29.9 ± 1.3	< **0.0001**
	e	de	cde	bcde	bcd	abc	ab	b	ab	ab	a	

a Values are presented in the form of "mean ± 1 standard error."
b Includes all aspen, not only those as tall or taller than the target pine.
c Tall aspen density refers to the density of aspen as tall or taller than the target lodgepole pine in the measurement year.
d Values in **bold type** are significant at $p \leq 0.05$, according to ANOVA. Means having different letters are significantly different within the given year. Mean separation was done with the Bonferroni test.

(a)



(b)

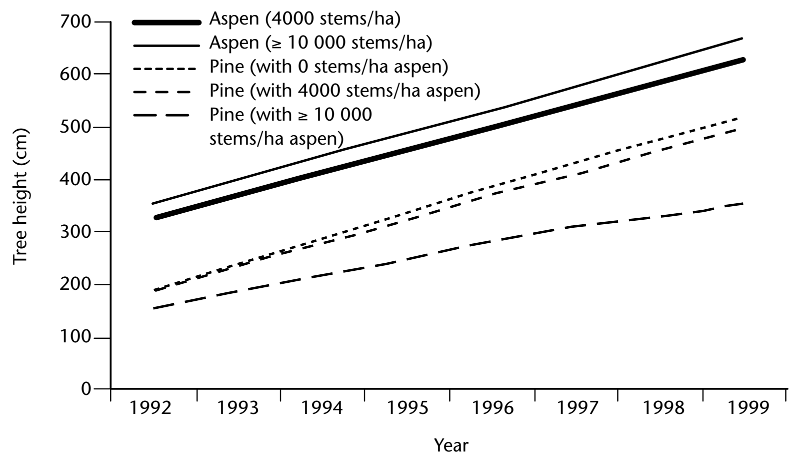


FIGURE 10 *Mean 1992–1999 height growth at (a) SBSdw sites and (b) IDFdk sites, among lodgepole pine in 0, 4000, and ≥ 10 000 stems per hectare tall aspen density classes, and aspen in 4000 and ≥ 10 000 stems per hectare density classes. Values were interpolated between measurement years.*

(Figure 12, Table 19). In the SBSdw, percent light was significantly higher where no tall aspen occurred than where tall aspen density was 10 000 or more stems per hectare. Other statistically significant differences were evident, but these did not follow a consistent trend, mainly because light levels were more variable within some tall aspen density classes than others. Light levels at the SBSdw sites ranged between 82% in the 0 stems per hectare class and 31% in the ≥ 10 000 stems per hectare class. Light levels were somewhat higher at IDFdk than SBSdw sites in respective density classes, ranging from 90% in the 0 stems per hectare class to 44% in the ≥ 10 000 stems per hectare class. At the IDFdk sites, light availability was significantly lower in the ≥ 10 000 stems per hectare class than the ≤ 2000 stems per hectare classes. Light levels in the 8000 and 9000 stems per hectare classes were also significantly lower than in the 0 stems per hectare class. Regardless of significant differences among classes, however, there were consistent trends of decreasing light availability with increasing tall aspen density at both the SBSdw and IDFdk sites.

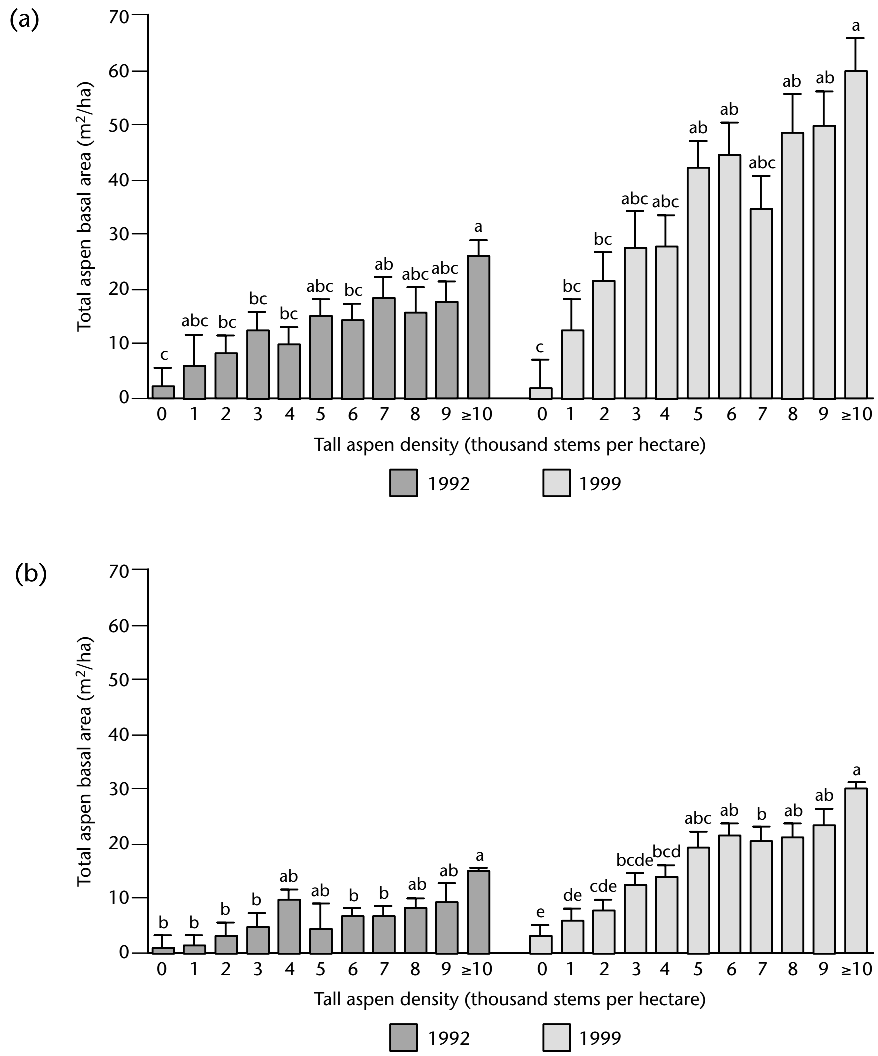


FIGURE 11 *Mean total aspen basal area (± 1 standard error) among tall aspen density classes at (a) SBSdw sites and (b) IDFdk sites in 1992 and 1999. Density classes are based on aspen as tall or taller than the target pine in the measurement year. Means having the same letter within a single year are not significantly different from one another according to the Bonferroni test ($p > 0.05$).*

3.4.3 Neighbourhood Size and Spatial Relationships between Pine and Aspen In 1999, the size of the neighbourhood in which aspen were competing with 15–19 year old target lodgepole pine was examined. Spearman's rank correlations between lodgepole pine diameter growth and leader length versus tall aspen density were examined for three different-sized neighbourhoods around the target pine.

According to calculated Spearman's rank correlation coefficients, increasing the size of the plots in which neighbourhood measurements were made (from 10 to 50 m^2) did not increase the correlation between tall aspen density and pine diameter growth or leader length. For this reason, no further analysis was completed (Table 20). The current analysis shows that measurements taken within a 1.78-m radius around target pine provide a reasonable

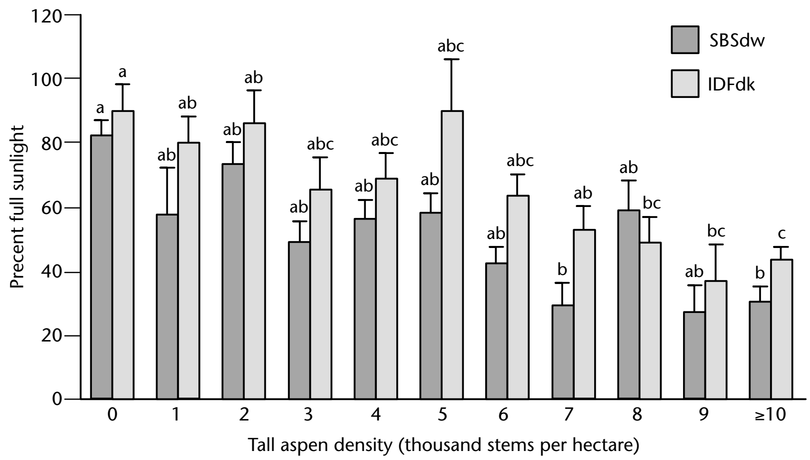


FIGURE 12 *Mean percent full sunlight (± 1 standard error) in tall aspen density classes at SBSdw and IDFdk sites in 1992. Density classes were based on aspen as tall or taller than the target pine in 1992. Means having the same letter for the same subzone are not significantly different from one another according to the Bonferroni test (p > 0.05).*

measure of pine–aspen competition in 15- to 19-year-old stands, but the size of the competitive neighbourhood may change as stands age or if the height differential increases.

3.4.4 Aspen Clumping In 1999, the spatial distribution of aspen was investigated to determine whether aspen in clumps (i.e., aspen growing within 30 cm of each other) should be treated as several individual trees or as a single tree. Spearman's rank correlations between lodgepole pine diameter growth and leader length versus tall aspen density were compared, counting aspen in clumps as a single tree or as individual trees. Three plot sizes were investigated (10 m^2, 20 m^2, and 50 m^2), but correlations were consistently higher in the smallest plot size and, therefore, data are only shown for the 10-m^2 plots (Table 21). A slightly stronger correlation existed between 15- to 19-year-old pine size and tall aspen density when aspen in clumps were counted as individuals than when each clump was counted as a single tree. This suggests that each of the aspen stems was contributing to competition, regardless of spatial distribution.

4 DISCUSSION

This working paper presents results from a retrospective study that was designed to investigate competitive interactions between trembling aspen and lodgepole pine in the Cariboo–Chilcotin area of the Southern Interior Forest Region. The study sites were located in the SBSdw and IDFdk subzones, within the Cariboo–Chilcotin moist-transition and dry-belt, respectively. The study assessed performance of lodgepole pine across a range of natural aspen densities and investigated the predictive ability of various competition indices and other measures of aspen abundance. In this discussion, we summarize our results and compare them with findings from other experiments.

TABLE 19 *Mean[a] percent full sunlight under the aspen canopy[b] in 1992 at the SBSdw and IDFdk sites*

	Tall aspen density[c]											
Stems per plot (r = 1.78 m)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**≥ 10**	
Stems per hectare	**0**	**1000**	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**> 10 000**	**p-value[d]**
SBSdw	82 ± 5	58 ± 15	73 ± 7	49 ± 7	56 ± 6	58 ± 7	42 ± 6	29 ± 8	59 ± 10	27 ± 9	31 ± 5	**0.0039**
	a	ab	ab	ab	ab	ab	ab	b	ab	ab	b	
IDFdk	90 ± 7	80 ± 8	86 ± 10	66 ± 10	69 ± 7	90 ± 16	63 ± 7	53 ± 7	49 ± 8	37 ± 12	44 ± 4	< **0.0001**
	a	ab	ab	abc	abc	abc	abc	ab	bc	bc	c	

a Values are presented in the form of "mean ± 1 standard error."
b Light measurements were taken at two-thirds the height of target pine, at the edge of the crown.
c Tall aspen density refers to the density of aspen as tall or taller than the target lodgepole pine in 1992.
d Values in **bold type** are significant at $p \leq 0.05$, according to ANOVA. Means having different letters are significantly different within the given year. Mean separation was done with the Bonferroni test.

TABLE 20 *Spearman's rank correlation coefficients for pairings of tall aspen density in 10-, 20-, and 50-m² plots with 1992–1999 lodgepole pine stem diameter increment and 1999 leader length*

	SBSdw					IDFdk				
			***R*[a]**					***R***		
	Site	***n***	**10 m² (r =1.78 m)**	**20 m² (r =2.52 m)**	**50 m² (r =3.99 m)**	**Site**	***n***	**10 m² (r =1.78 m)**	**20 m² (r =2.52 m)**	**50 m² (r =3.99 m)**
1992–1999 stem diameter increment										
	Hayfield	25	–0.6319	–0.5793	–0.6155	Moffatt	27	–0.5394	–0.5724	–0.5509
	Two-mile	18	–0.7617	–0.4247	–0.6279	Meldrum	26	–0.7151	–0.6470	–0.7031
1999 leader length										
	Hayfield	25	–0.6440	–0.5657	–0.5682	Moffatt	27	–0.1197	0.0072	–0.0323
	Two-mile	18	–0.6547	–0.3972	–0.5091	Meldrum	26	–0.6221	–0.4946	–0.4915

a *R* is the Spearman's rank correlation coefficient. Negative correlations improve as R decreases from 0 to –1; positive correlations improve as *R* increases from 0 to +1.

TABLE 21 *Spearman's rank correlation coefficients for pairings of tall aspen density[a] with 1992–1999 lodgepole pine stem diameter increment and 1999 leader length, where aspen clumps[b] were counted as either several individual trees or as a single tree*

	SBSdw				**IDFdk**			
			***R*[c]**				***R***	
	Site	***n***	**Aspen in clumps counted as individual trees**	**Clumps counted as single trees**	**Site**	***n***	**Aspen in clumps counted as individual trees**	**Clumps counted as single trees**
1992–1999 stem diameter increment								
	Hayfield	25	–0.6319	–0.6397	Moffatt	27	–0.5394	–0.4529
	Two-mile	18	–0.7617	–0.6727	Meldrum	26	–0.7151	–0.6793
1999 leader length								
	Hayfield	25	–0.6440	–0.6394	Moffatt	27	–0.1197	–0.0705
	Two-mile	18	–0.6547	–0.5185	Meldrum	26	–0.6221	–0.5620

a Density was assessed in 10-m^2 plots around the target pine.
b Aspen closer than 30 cm from each other (outside bark to outside bark) were considered as part of a clump.
c *R* is the Spearman's rank correlation coefficient. Negative correlations improve as *R* decreases from 0 to –1; positive correlations improve as *R* increases from 0 to +1.

We also make operational recommendations for prescribing levels of aspen retention that will not negatively affect lodgepole pine performance.

4.1 Aspen Stand Characteristics

Stands of trembling aspen commonly regenerate following clearcut logging in many parts of interior British Columbia. Although no formal comparisons have been made across biogeoclimatic zones, the characteristics of these stands and interactions between aspen and conifers appear to vary from region to region. In our retrospective study, we documented a number of differences in aspen stand characteristics between the SBSdw and IDFdk subzones.

Total aspen density relative to total aspen cover in our 7- to 12-year-old stands was higher at the IDFdk sites than the SBSdw sites. For example, in neighbourhoods where aspen cover averaged 11–15%, total aspen density in the IDFdk averaged 23 830 stems per hectare compared with 11 410 stems per hectare in the SBSdw. We initially intended to define competition classes on the basis of aspen cover, but it was soon clear that this method was not viable. Even in areas where at least 10 tall aspen occurred within a 10-m^2 plot, aspen cover averaged only 11% in the IDFdk and 27% in the SBSdw. This made it difficult to differentiate between cover classes. Accurate estimation of cover is also more difficult for a species such as aspen, which has small, randomly oriented leaves (Chen et al. 1997), than for a species such as thimbleberry (*Rubus parviflorus*), which has larger, horizontally oriented leaves.

Aspen on our SBSdw sites were considerably taller and had larger stem diameters than those of approximately the same age on the IDFdk sites. In the SBSdw, aspen in all tall aspen density classes were increasing in height at a faster rate than pine, whereas in the IDFdk, pine in neighbourhoods with 5000 or more tall aspen stems per hectare were growing at approximately the same rate as aspen. Simard et al. (2001) assessed aspen stands in the Interior Douglas-fir and Montane Spruce biogeoclimatic zones, further south than our study sites, and also found aspen were gaining in height over lodgepole pine at age 7–10 years. Relative height of aspen and pine is a particularly important consideration because of the low shade tolerance of pine and the steep declines in diameter growth that can be anticipated at reduced light levels (Wright et al. 1998).

4.2 Resource Competition in Pine–Aspen Stands

In juvenile broadleaf–conifer mixtures, light is generally considered to be the resource most limiting to conifer seedling growth (e.g., Burton 1993). Light availability is particularly important in aspen–lodgepole pine stands because both species are very shade intolerant (Klinka and Scagel 1984a, 1984b). We determined percent full sunlight under the aspen canopy when our stands were 7–12 years old. At both the IDFdk and SBSdw sites, light availability decreased gradually as tall aspen density increased. At all tall aspen densities, light levels were consistently higher in the IDFdk than the SBSdw. This implies that leaf area index (LAI) was lower in the IDFdk than the SBSdw, possibly because of the drier site conditions. Messier et al. (1998) suggested that aspen stands of equivalent basal area, density, and height may reduce understorey light availability more on moist than dry sites because LAI is higher on the moister sites. Our results show that aspen on the SBSdw sites contributed greater percent cover per tree than those on the IDFdk sites (see Section 4.1), which implies greater LAI per aspen tree in the moist SBSdw than the drier IDFdk.

Although light levels at our study sites decreased significantly from the lowest to the highest tall aspen density classes, the decrease was gradual and variability within density classes was high. For this reason, only the 0 and ≥ 10 000 tall aspen density classes were significantly different from each other. Wright et al. (1998) reported that lodgepole pine is very responsive to reductions in light at the high end of the light availability scale, with losses of up to 50% of maximum radial increment occurring where light availability was reduced to 38–50% of full sunlight. In our study, light availability in SBSdw and IDFdk neighbourhoods where tall aspen density exceeded 10 000 stems per hectare was reduced to 31 and 44% of full sunlight, respectively. In the 7 years following the 1992 light measurements, pine diameter increments in the ≥ 10 000 stems per hectare class in the SBSdw and IDFdk were 72 and 69% less than for pine growing in neighbourhoods with no tall aspen.

Comeau (2002) studied the relationship between aspen basal area and understorey light in 12- to 40-year-old aspen stands in the Boreal White and Black Spruce (BWBS) biogeoclimatic zone, and determined that light levels were below 60% full sunlight where aspen basal area exceeded 8 m^2/ha and below 40% full sunlight where aspen basal area exceeded 14 m^2/ha. He found that aspen basal area explained approximately 92% of the variation in understorey light, and that the relationship improved slightly when aspen density was included in the regression model. In another study involving juvenile aspen crown and light transmission characteristics, Pinno et al. (2001) were able to predict approximately 70% of the variation in 1- to 30-year-old aspen crown size and leaf area from aspen stem diameter at a height of 30 cm. However, the model did not improve with the addition of density as an independent variable. In the Comeau (2002) study, aspen density alone was a poor predictor of understorey light, whereas Tanner et al. (1996) found it highly successful ($R^2 = 0.87$) in older (50–80 years) aspen stands. This suggests that the size of individual aspen trees, including the crown dimensions and leaf density, becomes more homogeneous as stands age. Pinno et al. (2001) noted that crown overlap among aspen trees declined as stem diameter, and presumably age, increased. Our measurements in 7- to 12-year-old stands showed that light availability at the SBSdw sites declined below 60% where basal area exceeded approximately 10 m^2/ha, which occurred in the ≥ 3000 tall aspen stems per hectare density classes. At the IDFdk sites, light availability declined below 60% where basal area was greater than 6.5 m^2/ha, which occurred in the ≥ 7000 tall aspen stems per hectare density class. Light availability was never below 40% in the IDFdk; in the SBSdw, it was consistently below 40% only where tall aspen density exceeded 9000 stems per hectare and tall aspen basal area exceeded 17 m^2/ha. The relationship between aspen basal area and light availability clearly varies between the SBS, IDF, and BWBS biogeoclimatic zones, illustrating the need to study competitive relationships on an ecosystem-specific basis.

Soil moisture availability may also play an important role in competition on dry-belt pine–aspen sites, such as those in the IDFdk in this study. Studies in boreal ecosystems have shown that soil water is reduced by the presence of aspen. In the BWBS zone, Coopersmith et al. (2000) found the July–October soil water content under a 12-year-old aspen stand with a density of 10 000 aspen stems per hectare was approximately one-half that of an area where all aspen had been removed. In another study, soils below a 15-year-old alder, willow and aspen, stand in the boreal region of northern British Columbia had soil water potentials of –2 MPa for more than a month during a dry year, while water potentials rarely fell below –0.8 MPa in areas with no broadleaves and tall shrubs (L. Bedford, B.C. Ministry of Forests, pers. comm., 2001). Water potentials of –1.5 MPa are commonly considered to be the permanent wilting point for plants although conifers are likely to tolerate lower values (Kozlowski and Pallardy 1997). We did not measure soil water availability in our study, but based on the biogeoclimatic ecosystem classification, IDF sites typically have a soil-moisture deficit for 30–60 days each year (Klinka et al. 1984) and tend to have abundant pinegrass in the understorey (Steen and Coupé 1997). Pinegrass is an efficient competitor for soil moisture and has been shown to contribute to competition on IDFdk sites in the Cariboo–Chilcotin (Nicholson 1989).

4.3 Determining Thresholds for Aspen Retention

Current objectives for managing pine–aspen sites in the Cariboo–Chilcotin area of the Southern Interior Forest Region often include the achievement of acceptable lodgepole pine growth rates while maintaining an aspen component. Although softwood timber production may be the primary objective, biodiversity, wildlife values, pest and disease control, and long-term productivity are also important considerations—all of which are enhanced by the retention of aspen within these stands. Various studies have shown that aspen can provide short- and long-term benefits to sites by maintaining productivity (e.g., Pearson and Lawrence 1958; Pastor 1990; Prescott et al. 2000), slowing the spread of root disease (Morrison et al. 1991; Peterson and Peterson 1995), improving microclimate for conifer growth (DeLong et al. 2000), and increasing resistance to windthrow (Frivold 1985; Yang 1989). To achieve balance in their management prescriptions, silviculturists need to know how much aspen can be retained without incurring unacceptable conifer growth losses.

One approach to defining acceptable levels of aspen retention in lodgepole pine stands is to identify a measure of aspen abundance, or a measure of the relative position of aspen and pine stems that can successfully predict pine size in a regression model. The level of aspen abundance at which pine size is reduced below an acceptable level can then be identified and used to develop treatment prescriptions. Either individual aspen variables or multivariable competition indices can be used to predict pine size. Individual variables tend to require less time-consuming data collection, which is an important operational consideration. We tested 20 individual variables that characterized vegetation abundance in our pine–aspen stands.

Of the individual vegetation abundance variables we tested, tall aspen density consistently had the strongest correlation with lodgepole pine stem diameter, height, and leader length. This was true of our study sites in both the SBSdw and IDFdk subzones. Other variables that took aspen density into account (i.e., Σ stem-to-stem distance, Σ stem-to-crown distance, Σ basal area) were similarly well correlated with pine size, but are less easy to measure than density. Tall aspen density was better correlated with lodgepole pine stem diameter than with either height or leader length. When we compared the Spearman's rank order correlation coefficients calculated in our study with those calculated by Navratil and MacIsaac (1993), tall aspen density was more strongly correlated with lodgepole pine growth in the Cariboo–Chilcotin region of British Columbia than in the boreal region of northwestern Alberta. Spearman's rank correlation coefficients for pairings of aspen density with pine height, height increment, and basal area were consistently around -0.25 in the Alberta study, whereas they ranged from –0.25 to –0.82 for tall aspen density versus pine height, leader length, and stem diameter in our study. We found a slightly better correlation between tall aspen density and pine size at the SBSdw sites than the IDFdk sites.

We fitted a non-linear regression model to our data using tall aspen density as the independent variable, and were able to predict 40–65% and 37–43% of the variation in stem diameter of 7- to 12-year-old pine for sites in the SBSdw and IDFdk subzones, respectively. When stands were 15–19 years old, tall aspen density explained 48–64% and 50–63% of the variation in 1999 stem diameter on the SBSdw and IDFdk sites, respectively. The increase in R^2 values from 1992 to 1999 for the IDFdk sites suggests that the importance of competition between pine and aspen was increasing with stand age in that subzone, and may continue to do so. Tree growth rates were slower in the IDFdk than the SBSdw subzone sites, and the effects of competition may have been taking longer to express themselves.

We also used our retrospective data to test the ability of various competition indices to predict lodgepole pine size. Burton (1993) defines a competition index as a characterization of the degree to which the growing space of a plant is shared by other plants, but cautions that competition indices have inherent limitations because they are static one-time measurements. Indeed, conditions and competitive relationships within the plant community are constantly changing. One of Burton's recommendations is that competition indices be calibrated and verified with local data before they are used.

We tested the Navratil and MacIsaac CI, which had been applied in young pine–aspen stands northwestern Alberta, as well as four indices developed by British Columbia researchers for species other than pine and aspen. Competition indices may include both crop and competing species variables (in this case, pine and aspen variables), or be based on competing species variables alone. Competition indices that include a crop tree variable to predict crop tree size produce artificially inflated correlation coefficients compared with those that include only variables related to competing vegetation, but can provide a useful operational measure of the relative size of crop and competing trees at a given point in time. Of the five most highly correlated CIs we tested, only the Simard CI did not include a pine variable.

Navratil and MacIsaac (1993) found their own competition index (CI = tallest aspen basal diameter/target pine basal diameter)[4] was consistently more highly correlated with pine growth than indices developed by other researchers. Regression analysis showed it accounted for 55 and 51% of the variation in stem diameter among 5- to 10- and 11- to 16-year-old lodgepole pine, respectively. On our SBSdw sites, we also found the Navratil and MacIsaac CI had a higher correlation with pine size than the other indices. Regression analysis showed it explained 62–77% of the variation in stem diameter among 7- to 12-year-old pine. On our IDFdk sites, the closely related Lorimer CI [CI = Σ(aspen diameter / target pine diameter)] was most highly correlated with pine stem diameter, explaining 51–59% of the variation.

Navratil and MacIsaac (1993) analyzed the relationship between pine basal area increment and their CI values, and concluded that stand-tending activities in young stands should be directed at reducing the CI below 0.75. Operationally, this could be accomplished by removing all aspen that had basal stem diameters greater than 75% of the target pine diameter, within a 1.78-m radius of the pine. Similar analysis of Cariboo–Chilcotin data showed

4 Navratil and MacIsaac (1993) refer to this index as the Basal Diameter Ratio. In this paper, we refer to it as the "Navratil and MacIsaac Index."

that pine stem diameter declined relatively steeply at Navratil and MacIsaac CI values of 1.1 in the SBSdw and 1.5 in the IDFdk. This implies that pine would benefit by the removal of aspen with stem diameters exceeding 110% in the SBSdw and 150% in the IDFdk of the target pine stem diameter, within a 1.78-m radius of the target pine. However, management objectives concerning stand structure and wildlife values should be considered before brushing treatments are prescribed on the basis of the Navratil MacIsaac CI, as this treatment could result in all tall aspen being removed, depending on the relative diameters of aspen and pine in individual stands. Applying this CI on a microsite-specific basis during operational brushing is also potentially difficult because of the need for workers to visually estimate pine–aspen diameter ratios.

Using a similar approach with the Lorimer CI, pine stem diameter declined sharply at CI = 3.0 in the SBSdw and CI = 3.75 in the IDFdk. It is more difficult to derive operational recommendations using the Lorimer CI, however, because it depends both on aspen density and the relative diameter of pine and aspen. Figure 13 illustrates combinations of tall aspen density and pine–aspen stem diameter ratio that would yield the critical CI values in the two subzones. For example, if 7- to 12-year-old tall aspen and pine had equal stem diameter (i.e., the aspen–pine stem diameter ratio was equal to 1), then the recommended operational treatments would retain three tall aspen within a 1.78-m radius of the target pine in the SBSdw, and 3.75 tall aspen within a 1.78-m radius in the IDFdk.

The Simard CI was also reasonably successful for predicting lodgepole pine stem diameter, considering that it did not include a measure of lodgepole pine size. Instead, it was based on aspen height, the spatial relationship between aspen and pine, and aspen density. The Simard CI explained 29–63% of the variation in pine stem diameter on SBSdw sites and 18–40% of the variation on IDFdk sites. Simard (1990) originally developed this CI for juvenile stands of birch and Douglas-fir in southern interior British Columbia, where it explained 41–51% of the variation in Douglas-fir stem diameter.

Another approach to defining a competition threshold involves visually fitting a maximum response curve (encompassing 95% of observations) to a

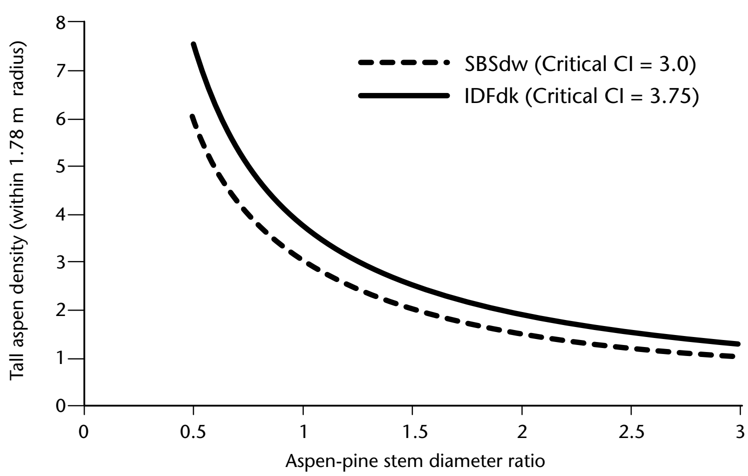


FIGURE 13 *Combinations of aspen–pine stem diameter ratio and tall aspen density (within a 1.78 m radius of pine) that would produce Lorimer CI values of 3.0 in 7- to 12-year-old stands in the SBSdw and 3.75 in the IDFdk.*

scatter plot of conifer response versus the abundance of vegetation within the immediate neighbourhood. Using this method, Simard et al. (2001) identified an aspen density threshold of 3180 stems per hectare for stem diameter growth of 2- to 10-year-old lodgepole pine in the MS and IDF zones of southern interior British Columbia. All aspen stems, not just those taller than the target pine, were included in the threshold value. We have not identified competition thresholds by this method, but analysis of pine performance by density class provides similar information.

We used ANOVA to compare lodgepole pine size at tall aspen densities ranging from 0 to ≥ 10 000 stems per hectare. Our results showed that the competitive relationship between aspen and lodgepole pine was somewhat different at the SBSdw and IDFdk sites. In both subzones, a tall aspen density range could be identified where pine performance declined noticeably, but the critical densities were lower at the SBSdw sites than the IDFdk sites. The apparent lower competitive ability of aspen at the IDFdk compared to the SBSdw sites is possibly related to the drier climate. Aspen trees have less tolerance than pine for dry sites (Klinka and Scagel, 1984a and 1984b), and have been observed to develop poorly on sites that are excessively droughty (Fowells 1965). Alternatively, competitive effects may simply be manifesting more slowly in the IDFdk than the SBSdw because of the slower growth of both aspen and pine.

Pine stem diameter was a more responsive variable than pine height to density changes in both subzones, which is consistent with our correlation and regression analysis results. DeLong (1991) also found that conifer stem diameter was more responsive than height to natural differences in vegetation abundance. Likewise, numerous brushing studies have shown that diameter responds more quickly than height to treatment-induced reductions in vegetation abundance (e.g., Lanner 1985; Lanini and Radosevich 1986; Simard et al. 2001).

In our study, tall aspen density clearly affected pine performance, and the effects became more pronounced as stands aged. In 1999, when SBSdw stands were 17–18 years old, pine stem diameter was significantly smaller in neighbourhoods with more than 1000 stems per hectare (> 1 tall aspen within 1.78 m of the target pine) than in neighbourhoods with no tall aspen. At the IDFdk sites, decreases in pine diameter were evident where tall aspen density exceeded 2000 stems per hectare, but the threshold was less distinct than at the SBSdw sites. Significant differences in IDFdk pine diameter, relative to neighbourhoods with no tall aspen, became apparent over the range of 3000–5000 tall aspen stems per hectare (3–5 stems within 1.78 m of the target pine). Visual examination of the data (Figure 6) shows a definite decrease in diameter above 1000 stems per hectare in the SBSdw and a more gradual decrease in the IDFdk. For purposes of comparison with the Simard et al. (2001) study, total aspen densities in the 1000 and 2000 tall aspen stems per hectare classes in the SBSdw and IDFdk, respectively, were 9703 and 6750 stems per hectare.

Pine vigour declined between 1992 and 1999 in both subzones and, again, trends were more pronounced in the SBSdw than the IDFdk. In 1999, trends in pine vigour agreed with trends in stem diameter in both subzones. At the SBSdw sites, the proportion of pine either dead or of poor vigour increased in neighbourhoods with greater than 1000 tall aspen stems per hectare, whereas at the IDFdk sites, this did not occur until at least 5000 tall aspen stems per hectare were present. In both subzones, however, the majority

(70–80%) of 15- to 19-year-old pine were in good vigour only in neighbourhoods where tall aspen density was less than 2000 stems per hectare. This also supports our interpretation that the effects of competition are manifested more slowly in the IDFdk than in the SBSdw.

Height-to-diameter ratio was strongly affected by increasing tall aspen density in our study, but consistent trends emerged more slowly than for stem diameter. Trends also manifested more slowly in the IDFdk than the SBSdw. For 15- to 19-year-old pine growing in neighbourhoods with no tall aspen, average HDR values were 55 and 56 for the IDFdk and SBSdw, respectively. In the MS and IDF zones near Kamloops, B.C., Simard et al. (2001) found a similar HDR value of 56 for 10- to 13-year-old pine growing in neighbourhoods where all aspen had been removed. However, acceptable HDR values change with tree age and differ between ecosystems and perhaps even sites. In our study, trends in pine diameter and vigour suggest threshold values of 1000 and 2000 tall aspen stems per hectare in the SBSdw and IDFdk, respectively, and HDR values in those density classes were 61 and 60 when stands were 15–19 years old.

In both subzones that we studied, the presence of even one tall aspen within a 1.78-m radius of target pine caused HDR to increase. In the SBSdw, substantial increases were evident in 1999 HDR as neighbourhood tall aspen density increased to 2000 and 3000 stems per hectare (i.e., 2 and 3 tall aspen within a 1.78-m radius). By the time pine in our study were 15–19 years old, those in the SBSdw showed a consistent trend of increasing HDR with increasing tall aspen density. Pine in the IDFdk were not showing consistent trends in HDR at that age, especially in low-density classes; values fluctuated between density classes up to 4000 stems per hectare, after which they increased gradually with increasing tall aspen density. Since pine diameter growth did not consistently decline in the IDFdk until tall aspen density reached 5000 stems per hectare, the large increases in HDR in the 1000 and 3000 tall aspen stems per hectare classes may indicate a shift in resource allocation from branch production to height growth. However, this growth trend is generally associated with lower light environments (Chen et al. 1996) than those observed in the 1000–3000 stems per hectare classes in this study. At the SBSdw sites, a similar pattern of fluctuating HDR was observed in 1992, but not 1999. This, again, indicates that the effects of competition were expressing themselves more slowly in the IDFdk than the SBSdw.

4.4 Neighbourhood Size, Spatial Arrangement of Aspen, and Height of Competing Aspen

We collected detailed information regarding neighbourhood size and the spatial arrangement of aspen according to height classes, but these data have not yet been extensively analyzed. On the basis of correlation analysis, 10-m^2 plots seem to provide a reasonable measure of competition between 15- to 19-year-old lodgepole pine and tall aspen. The inclusion of tall aspen growing at distances up to 2.52 and 3.99 m from the target pine did not improve the correlation between aspen density and pine stem diameter. In contrast to this, Lieffers et al. (2002) found that plots of less than 2-m radius did not provide a good representation of light competition between aspen and white spruce. In their stands, understorey light was minimized when aspen were 10- to 12-m tall, and they suggest plots of 10-m radius would be required to assess understorey light conditions at that stage of stand development. Simard and Sachs (in preparation) also found that size of the competitive neighbourhood in 11-year-old Douglas-fir and paper birch stands in the ICHmw subzone of the Kamloops area of the Southern Interior Forest Region was larger than we found for aspen and pine. In their study, broadleaves up to 3–4 m from the target conifers were contributing to competition. The apparently smaller neighbourhood size observed in our study, compared with the Lieffers et al. (2002) and Simard and Sachs studies, could be attributed to the smaller height differential between conifers and broadleaves at our study sites; larger height differentials in the aspen–spruce and birch–Douglas-fir stands would have allowed broadleaves to shade conifers from a greater distance. Pine is more shade intolerant than Douglas-fir or white spruce and is, therefore, less likely to survive over the long term when it is severely overtopped. In our study, pine were growing within the aspen canopy rather than below it, with a height differential between aspen and pine of 1.5–4 m. Light levels within aspen stands increase rapidly from the base to the top of the canopy, so that conifers that have achieved 40% of the canopy height receive approximately 80% full sunlight (Comeau 2002).

In the Simard and Sachs (in preparation) study, birch 3–4 times as tall as the target Douglas-fir were the most important competitors in 11-year-old stands, whereas shorter competitors were more important in 25- and 50-year-old stands. This suggests that competition was mainly for light in young stands, but shifted to soil resources as stands aged and Douglas-fir gradually surpassed broadleaves in height. In our study, aspen stems as tall or taller than the target pine were the most important competitors in 7- to 12-year-old stands in both the SBSdw and IDFdk subzones. This finding suggests that light was the most limiting resource in both subzones, but the slightly weaker correlation between density and pine growth at the IDFdk than the SBSdw sites implies greater importance of other factors (probably soil moisture availability) in the former. Given that pine and aspen are both shade intolerant (Klinka and Scagel, 1984a and 1984b), and that aspen are increasing in height as fast or faster than pine, light will likely continue as the most limiting resource on our sites for many years.

4.5 Management and Operational Recommendations

This study provides information about the competitive effects of trembling aspen on lodgepole pine at various tall aspen densities in the SBSdw and IDFdk subzones. The findings will help forest managers to decide whether reductions in aspen density are necessary to enhance lodgepole pine vigour and growth, and to prescribe appropriate densities of aspen when brushing treatments are considered. We observed differences in the pine–aspen competitive process between the moister SBSdw and drier IDFdk subzones and have, therefore, provided separate recommendations for these two subzones.

In addition to biological considerations, forest managers must also consider treatment costs. Our study results should assist managers to use treatment dollars as effectively as possible. Policy makers can also use this information to determine free-growing criteria.

The operational recommendations presented below are based on our study results for stands in the SBSdw and IDFdk subzones. They are preliminary and may therefore not agree with the present free-growing guidelines for the Cariboo–Chilcotin area of the Southern Interior Forest Region. Current free-growing guidelines have set maximum densities of "countable" aspen (countable aspen generally equate with "tall" aspen in this study) on zonal sites at 400 stems per hectare in the SBSdw and 1000 stems per hectare in the IDFdk (B.C. Ministry of Forests 2002). The free-growing guidelines are intentionally conservative to ensure that good conifer performance will continue through a full rotation; however, we have also been conservative in our recommendations so that a decline in conifer performance can be avoided if competition effects increase as stands age beyond 15–19 years. For instance, we observed that the effects of aspen competition on pine growth increased between 1992 and 1999. Had we made recommendations on the basis of data collected when stands were 7–12 years old (a range of ages when free growing assessments are commonly made in British Columbia), we would have suggested higher thresholds for aspen retention than those we make based on the 1999 data. Therefore, management recommendations may change further as future retrospective measurements provide information about stand development and the changes in the competitive relationship between aspen and pine.

1. Data for this study were collected in 10-m^2 (1.78-m radius) plots. We emphasize that the results should be applied on a microsite-specific basis and not at the stand level. Other studies are currently investigating stand-level effects of pine–aspen competition (Newsome 1999).
2. The results are specific to pine–aspen stands in the SBSdw1 and IDFdk3/dk4, and require further testing before they can be applied to other ecosystems.
3. Prescriptions to reduce aspen density should focus on aspen as tall or taller than the target pine. We found shorter aspen did not seriously reduce pine performance in 7- to 19-year-old stands in the SBSdw and IDFdk subzones.
4. In the SBSdw, no more than one tall aspen (1000 stems per hectare) should be left within a 1.78-m radius of the crop pine when the stand is 7–10 years old. We found that although the effects of aspen competition on pine were only weakly apparent when stands were 7–12 years old, they become much more pronounced by age 17-18 years in neighbourhoods where tall aspen density exceeded 1000 stems per hectare.
5. If the Navratil and MacIsaac CI is applied in the SBSdw, then brushing treatments should remove all aspen with diameters greater than 110% of the target pine stem diameter within 1.78 m of the target pine. For operational purposes, brushing crews could be instructed to remove all aspen with diameters larger than that of the target pine within a 2-m radius. Managers should be aware that, since aspen height generally increases with diameter, this approach could result in the majority of tall aspen being removed from the stand.
6. As a conservative recommendation in the IDFdk, no more than two tall aspen (2000 stems per hectare) should be left within a 1.78-m radius of the crop pine when the stand is 7–10 years old. Results were more variable in the IDFdk than the SBSdw, and firmer recommendations will be made when longer-term results from a variable density study are available.
7. Alternatively in the IDFdk, brushing treatments should remove all aspen having diameters greater than 150% the target pine stem diameter, within 1.78 m of the target pine. This is based on the Navratil and MacIsaac CI, which had the second highest correlation with pine diameter growth for that subzone. The Lorimer CI had a higher correlation in the IDFdk, but it is more difficult to apply operationally. As in the SBSdw, this approach has the potential to result in the removal of the majority of tall aspen.
8. Operational brushing treatments should focus on aspen within a 2-m radius of target pine. Our results suggest that, up to stand ages of 15–19

years, the competitive effects of aspen on pine do not extend beyond a radius of 1.78 m. Aspen at greater distances can be retained, which may reduce brushing costs. The retention of aspen outside the competitive neighbourhood of individual pine will provide benefits to both individual aspen and the site as a whole.

9. We do not suggest critical HDR values for applying brushing treatments for the following reasons. First, trends in HDR were inconsistent in our study (especially in the IDFdk) which suggests that, without supporting information, it is not a reliable indicator of competition. Second, the results of this study should only be applied on a microsite-specific basis; it would be difficult to visually estimate HDR during the application of operational brushing treatments.

5 FUTURE WORK

This retrospective study has provided valuable information about competitive relationships in juvenile pine–aspen stands in the Cariboo–Chilcotin area of the Southern Interior Forest Region. However, further work is needed to fill gaps in our present understanding, to extend our knowledge to older stands, and to increase the confidence with which we can apply the results. Continued measurement of the study sites at 5- or 10-year intervals will provide valuable information about the development of pine–aspen stands as they age, and is potentially useful to modellers. Stand-level responses of lodgepole pine to varying aspen density are also extremely important, and are currently being investigated in other studies in the Cariboo–Chilcotin (e.g., Newsome 1999).

To ensure that management techniques provide long-term efficacy, the effects of stand age and changing differential in pine–aspen height on size of the competitive neighbourhood are of interest as well. This type of information will also help to refine free-growing and brushing guidelines. We have already collected extensive data relating spatial relationships in juvenile pine–aspen stands, but have not yet conducted a full analysis.

Other researchers have developed models for predicting light availability under and within aspen canopies from aspen stand parameters (e.g., Comeau 2002). We would like to test these relationships for Cariboo–Chilcotin stands and investigate their correlation with actual lodgepole pine responses. These models are currently of particular interest to managers in the development of treatment regimes for mixed stands.

Finally, with further data collection and analysis, we would like to determine whether individual sites can be combined in a single model that would apply across one or more biogeoclimatic units (e.g., as described by Ott [1997]). Testing these relationships in additional ecosystems would provide more information about the extent to which they could be applied to other ecosystems in the Cariboo–Chilcotin.

TABLE A1.1 *Distribution of retrospective study plots on SBSdw sites in 1992, 1994, and 1999[a]. Values in each cell are the plot identification numbers.*

	Tall aspen density[b]										
Stems per 10-m² plot	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**≥ 10**
Stems per hectare	**0**	**1000**	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**≥ 10 000**
Hayfield											
1992	7, 8, 13, 18, 19, 20 21, 31, 34		9, 12, 23, 40, 47	6, 44	1, 2, 5	48	3, 15, 24, 28, 37	4, 14, 32, 41		25, 43	10, 11, 16, 22, 26, 27, 29, 33, 35, 36, 38, 39, 42, 45, 46, 49, 50
1994	7, 8, 13, 18, 19, 20, 21, 31, 34	23, 56, 58, 60, 64, 65	9, 12, 40, 47, 55, 57, 61	6, 44, 41, 59, 63	1, 2, 5, 48, 41, 62, 66, 69	24, 28, 53, 68	3, 15, 37, 52	4, 14, 32, 54	25, 43, 49, 67	22, 38, 42, 29	10, 11, 16, 22, 26, 27, 35, 39, 45, 46, 50, 51
1999	7, 8, 13, 18, 19, 20, 21, 31, 34, 56, 58, 64	12, 47, 57, 60	6, 9, 40, 55, 61	44, 59	1, 2, 5	24, 25, 28, 30, 32, 37, 53	3, 15, 43, 52, 63	4, 14, 29, 54	38, 49	35, 42, 50, 51	10, 11, 16, 22, 26, 27, 33, 46, 51
Two-mile											
1992	10, 12, 13, 14, 17, 18, 26, 32	29	19, 30	1, 11, 44	5, 6, 16, 22, 31, 36, 46, 47	2, 8, 23, 27, 34, 38	3, 20, 21, 24, 25, 45, 50	7	9, 35, 37	49	15, 28, 38, 39, 41, 42, 43, 40
1994	10, 12, 13, 14, 17, 18, 26, 32, 33, 51, 60	29, 30, 54, 55, 62, 63	16, 19, 59, 64, 65, 67, 71	11, 52, 53, 66, 68	5, 6, 22, 23, 31, 36, 47, 56, 58, 70	1, 2, 8, 27, 34, 48, 61, 69	20, 21, 24, 45, 50	7, 35, 57	9, 37	15, 49	28, 38, 39, 41, 43, 40
1999	10, 12, 13, 14, 18, 26, 32, 33, 51, 60	19, 54, 55, 62, 63	29, 59, 64, 65, 67, 71	11, 16, 23, 44, 53, 58, 66	5, 6, 22, 31, 47, 52, 56	1, 2, 7, 8, 21, 27, 34 35, 48, 50, 61, 69, 70	9, 20, 45	37, 57	28, 49	38, 41	43, 49

Continued

TABLE A1.1 *(Continued)*

	Tall aspen density[b]										
Stems per 10-m² plot	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**≥ 10**
Stems per hectare	**0**	**1000**	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**≥ 10 000**
Oie Lake											
1992	11, 16, 17, 21, 27, 35, 37, 41, 50	29		3, 5		2, 26	36	12, 33	1, 22, 24, 30, 31	10, 28	4, 6, 7, 8, 9, 13, 14, 15, 18, 19, 20, 23, 25, 31, 32, 34, 43, 44, 45, 46, 49
1994	1, 11, 16, 17, 21, 27, 35, 37, 40, 41, 50	29, 59, 61	54, 56, 57, 58, 60	3, 5, 62, 64, 72, 73	2, 26, 52, 53, 55, 67	63, 65, 66, 68, 69, 70, 71	12, 36, 51	22, 24, 33	28	30, 38, 39, 42, 48	4, 6, 7, 8, 9, 13, 14, 15, 18, 19, 20, 23, 25, 31, 32, 34, 43, 44, 45, 46, 49

a The Oie Lake site was not measured in 1999.
b Tall aspen density refers to the density of aspen as tall or taller than the target lodgepole pine in the measurement year.

TABLE A1.2 *Distribution of retrospective study plots on IDFdk sites in 1992, 1997, and 1999*[a]

	Tall aspen density[b]										
Stems per 10-m² plot	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**≥ 10**
Stems per hectare	**0**	**1000**	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**≥ 10 000**
Moffatt											
1992	9	7, 18, 34	10, 50	17, 32	5	40	12, 16, 22	2, 13, 25, 35	8, 26, 29, 28, 36	48 47	1, 3, 4, 6, 14, 15, 19, 20, 21, 23, 24, 27, 30, 31, 33, 37, 38, 39, 41, 42, 43, 45, 46, 49
1997	9, 18, 34, 50, 53	5, 7, 17, 32, 40, 52, 55, 58, 59, 60	3, 10, 51, 54, 57, 61	2, 22, 26, 35, 47	12, 13, 28, 56	8, 16, 21, 36, 37	1, 4, 29	23, 25, 48, 43	6, 14, 39, 42	31, 46	15, 19, 20, 24, 27, 30, 33, 38, 41, 45, 49
1999	5, 9, 18, 34, 50, 58	17, 22, 32, 40, 52, 53, 59, 60	7, 10, 35, 51, 55, 54, 57, 61	2, 3, 12, 13, 25, 26	16, 47, 56	21, 28, 37	1, 8, 23, 29, 31, 36, 43	4, 14, 42, 48	6, 39	30, 38, 46	15, 19, 20, 24, 27, 33, 41, 45, 49
Meldrum											
1992	13, 26, 29, 48, 49	17, 28	12, 27	37	1, 30, 33, 36, 39		5, 14, 31	11	8	2	3, 4, 6, 7, 9, 10, 15, 16, 18, 19, 20, 21, 22, 23, 24, 25, 32, 34, 35, 38, 40, 41, 42, 43, 44, 45, 46, 47
1997	13, 17, 26, 29, 31, 37, 48, 49	33, 52, 55, 56, 59	1, 12, 27			36	5, 14, 15	16, 18	8, 32, 40	9, 41	2, 3, 4, 6, 7, 10, 19, 20, 21, 22, 23, 24, 25, 34, 35, 38, 42, 43, 44, 45, 46, 47

Continued

TABLE A1.2 *(Continued)*

	Tall aspen density[b]										
Stems per 10-m² plot	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**≥ 10**
Stems per hectare	**0**	**1000**	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**≥ 10 000**
Meldrum											
1999	13, 17, 26, 28, 29, 33, 37, 48, 49, 51, 53, 55, 56	52, 59	1, 12, 27, 58	30, 50	11, 36, 39, 54, 57	14, 51	5, 15	8, 16, 18	9, 10, 32, 40	41, 43	2, 3, 4, 6, 7, 11, 19, 20, 21, 22, 23, 24, 25, 34, 35, 38, 42, 44, 45, 46, 47
Raven											
1992	9, 15, 23, 32, 45	19	8, 25	42	12, 22, 39, 43	14	47	26, 33, 41	3, 29	10, 34	1, 2, 3, 4, 5, 6, 7, 11, 13, 16, 17, 18, 20, 21, 24, 27, 28, 30, 31, 35, 36, 37, 38, 40, 44, 46, 48, 49, 50
1997	9, 15, 19, 23, 32	53, 55	8, 12, 25, 28, 52, 59, 62, 63	22, 33, 42, 54, 57, 60, 61, 64	6, 14, 39, 41, 43, 51, 56	26, 45	34, 37	3	10, 11, 65	29, 49	1, 2, 4, 5, 7, 13, 16, 17, 18, 20, 21, 24, 27, 28, 30, 31, 36, 37, 38, 40, 44, 46, 48, 50

a The Raven site was not measured in 1999.

b Tall aspen density refers to the density of aspen as tall or taller than the target lodgepole pine in the measurement year.

APPENDIX 2 CARIBOO FOREST REGION SEEDLING ASSESSMENT CRITERIA

Overall Seedling Condition

Code	
1 Good	Seedling shows no signs of stress, has a vigorous growth rate and a generally healthy appearance.
2 Fair	Seedling is under some form of stress, may have minor defects and has a moderate growth rate.
3 Poor	Seedling is under severe stress, may have major defects, and the growth rate is poor.
4 Moribund	Seedling is almost dead.
5 Dead	
6 Missing	
7 Destructively Sampled	

Seedling Vegetation Cover Codes

O Overtopped	The leader of the crop tree is at present overtopped by surrounding vegetation; crop tree available sunlight is greatly reduced.
T Threatened	The leader of the crop tree is at or near the same height of the surrounding vegetation, and (or) is likely to be overtopped within two growing seasons.
F Free Growing	The leader of the crop tree is well above the surrounding vegetation and is not likely to become threatened.

Seedling Damage Codes

Stem Condition Code	**Foliage Condition Code**
H – No visible effect (healthy)	H – No visible effect (healthy)
P – Bark peeled or abraded	Y – Chlorotic (yellow)
B – Stem bent	M – Mottled
S – Stem smashed, crushed, trampled	N – Necrotic
C – Stem cut, clipped, broken	A – Needles absent, defoliated
D – Tree dead, dying	B – Browsed
M – Tree missing	D – Dead buds on lateral branches
F – Stem forked	G – Gall aphid
G – Gall rust	Ø – Other symptoms (specify)
Ø – Other symptoms (specify)	

Damage Cause Code

A – None
H – Herbicide
M – Mechanical equipment
T – Hand tools
S – Falling slash (human caused)
X – Falling or sliding debris
E – Climate – frost
N – Snow press
V – Vegetation press
W – Climate – drought
R – Rodents, small animals
B – Big game
L – Livestock
F – Fire
I – Insects
D – Disease
Z – Destructively sampled
G – Winter damage
P – Whipping damage
Ø – Other (specify)
U – Unknown

Leader Shoot Condition Code

H – No visible effect (healthy)
C – Curled
F – Forked
B – Browsed
T – Dead terminal bud
S – Snapped, broken
A – Absent, missing
P – Pissodes
Ø – Other symptoms (specify)
N – No or Abnormal Flush

TABLE A3.1 *Spearman's rank correlation coefficients for pairings of 1992 lodgepole pine stem diameter with vegetation abundance variables at the Hayfield, Two-mile, and Oie Lake sites in the SBSdw subzone*

Hayfield			Two-mile			Oie Lake		
	Ranking of variables[a,b]	*R*[c]		Ranking of variables	*R*		Ranking of variables	*R*
1	Tall aspen density	–0.7727	1	Tall aspen density	–0.7275	1	Tall aspen density	–0.8202
2	∑ stem-to-stem distance	–0.7524	2	∑ stem-to-stem distance	–0.7217	2	∑ stem-to-stem distance	–0.8010
3	Total tree cover	–0.7440	3	∑ stem-to-crown distance	–0.6480	3	∑ stem-to-crown distance	–0.7971
4	Total aspen cover	–0.7435	4	∑ aspen basal area	–0.6437	4	∑ aspen basal area	–0.7738
5	∑ aspen basal area	–0.7219	5	Total aspen cover	–0.5694	5	Total aspen cover	–0.6880
6	∑ stem-to-crown distance	–0.6852	6	Total tree cover	–0.5637	6	Total tree cover	–0.6781
7	Minimum stem-to-stem distance	0.5394	7	Diameter of tallest aspen	–0.4612	7	Diameter of tallest aspen	–0.5616
8	Maximum aspen height	–0.5148	8	Maximum aspen height	–0.4423	8	Maximum aspen height	–0.5399
9	Mean aspen diameter	0.4975	9	Herb cover	–0.4061	9	Minimum stem-to-stem distance	0.4623
10	Diameter of tallest aspen	–0.3997	10	Minimum stem-to-crown distance	0.2901	10	Mean aspen diameter	0.3746
11	Herb cover	–0.3952	11	Minimum stem-to-stem distance	0.2870	11	Mean stem-to-crown distance	–0.3589
12	Minimum stem-to-crown distance	0.3705	12	Mean aspen height	–0.2773	12	Minimum stem-to-crown distance	0.3261
13	Mean aspen height	–0.3567	13	Herb height	–0.2434	13	Maximum aspen diameter	–0.2692
14	Shrub cover	–0.2910	14	Shrub cover	–0.2299	14	Shrub height	–0.1928
15	Shrub height	–0.2829	15	Shrub height	–0.2130	15	Conifer cover	–0.1623
16	Herb height	–0.1830	16	Mean aspen diameter	0.1991	16	Mean aspen height	–0.1548
17	Mean stem-to-crown distance	–0.1574	17	Maximum aspen diameter	–0.1300	17	Herb cover	0.1495
18	Conifer cover	0.1032	18	Mean stem-to-crown distance	–0.1236	18	Herb height	–0.1122
19	Maximum aspen diameter	–0.0462	19	Conifer cover	–0.0339	19	Shrub cover	–0.0773
20	Mean stem-to-stem distance	–0.0328	20	Mean stem-to-stem distance	–0.0210	20	Mean stem-to-stem distance	0.0187

a Variables are ranked from 1 to 20 in order of decreasing absolute value for *R*.

b All variables relating to aspen include only aspen as tall or taller than the target pine (except "Total aspen cover").

c *R* is the Spearman's rank correlation coefficient. Negative correlations improve as *R* decreases from 0 to –1; positive correlations improve as *R* increases from 0 to +1.

TABLE A3.2 *Spearman's rank correlation coefficients for pairings of 1992 lodgepole pine stem diameter with vegetation abundance variables at the Moffatt, Meldrum, and Raven sites in the IDFdk subzone*

Moffatt			Meldrum			Raven		
Ranking of variables[a,b]		R[c]	Ranking of variables		R	Ranking of variables		R
1	Tall aspen density	–0.6068	1	Tall aspen density	–0.5888	1	Tall aspen density	–0.6773
2	∑ stem-to-crown distance	–0.5701	2	Mean aspen diameter	0.5770	2	∑ stem-to-stem distance	–0.6208
3	Minimum stem-to-stem distance	0.5361	3	∑ stem-to-stem distance	–0.5675	3	∑ aspen basal area	–0.6112
4	∑ stem-to-stem distance	–0.5296	4	∑ stem-to-crown distance	–0.5669	4	Minimum stem-to-stem distance	0.5987
5	Total tree cover	–0.5231	5	∑ aspen basal area	–0.4392	5	∑ stem-to-crown distance	–0.5916
6	Total aspen cover	–0.5001	6	Total aspen cover	–0.3939	6	∑ stem-to-crown distance	–0.5126
7	Minimum stem-to-crown distance	0.4988	7	Total tree cover	–0.3869	7	Total aspen cover	–0.4927
8	∑ aspen basal area	–0.3720	8	Minimum stem-to-crown distance	0.3174	8	Minimum stem-to-crown distance	0.4709
9	Mean aspen diameter	0.3421	9	Mean stem-to-crown distance	–0.2968	9	Total tree cover	–0.4418
10	Mean stem-to-stem distance	0.2516	10	Minimum stem-to-stem distance	0.2773	10	Mean aspen diameter	–0.4042
11	Mean aspen height	0.2404	11	Maximum aspen height	–0.2398	11	Mean stem-to-stem distance	0.3031
12	Herb height	–0.1947	12	Herb height	–0.2349	12	Herb cover	0.2161
13	Conifer cover	–0.1938	13	Shrub height	–0.1265	13	Diameter of tallest aspen	–0.2092
14	Shrub height	–0.1486	14	Mean stem-to-stem distance	–0.1124	14	Conifer cover	0.1882
15	Herb cover	–0.1296	15	Diameter of tallest aspen	–0.1035	15	Shrub cover	–0.1708
16	Mean stem-to-crown distance	–0.1062	16	Conifer cover	0.0962	16	Shrub height	–0.1386
17	Maximum aspen height	–0.0888	17	Herb cover	–0.0715	17	Maximum aspen diameter	–0.1159
18	Maximum aspen diameter	0.0587	18	Maximum aspen diameter	–0.0466	18	Mean stem-to-crown distance	–0.0732
19	Shrub cover	–0.0403	19	Mean aspen height	0.0367	19	Herb height	–0.0327
20	Diameter of tallest aspen	0.0305	20	Shrub cover	–0.0129	20	Mean aspen height	–0.0102

a Variables are ranked from 1 to 20 in order of decreasing absolute value for *R*.
b All variables relating to aspen include only aspen as tall or taller than the target pine (except "Total aspen cover").
c *R* is the Spearman's rank correlation coefficient. Negative correlations improve as *R* decreases from 0 to –1; positive correlations improve as *R* increases from 0 to +1.

TABLE A3.3 *Spearman's rank correlation coefficients for pairings of 1992 lodgepole pine height with vegetation abundance variables at the Hayfield, Two-mile, and Oie Lake sites in the SBSdw subzone*

Hayfield			Two-mile			Oie Lake		
Ranking of variables[a,b]		**R[c]**	**Ranking of variables**		**R**	**Ranking of variables**		**R**
1	Tall aspen density	0.7656	1	Tall aspen density	0.6788	1	Total tree cover	0.6237
2	∑ stem-to-stem distance	0.7367	2	∑ stem-to-stem distance	0.6526	2	Tall aspen density	0.6185
3	∑ aspen basal area	0.7252	3	∑ aspen basal area	0.6520	3	Total aspen cover	0.6183
4	∑ stem-to-crown distance	0.7180	4	Total aspen cover	0.6457	4	∑ stem-to-stem distance	0.5871
5	Total tree cover	0.7033	5	Total tree cover	0.6318	5	∑ stem-to-crown distance	0.5601
6	Total aspen cover	0.6990	6	Minimum stem-to-stem distance	–0.6210	6	∑ aspen basal area	0.5528
7	Maximum aspen height	0.5652	7	∑ stem-to-crown distance	0.5566	7	Minimum stem-to-stem distance	–0.4761
8	Mean aspen diameter	–0.5118	8	Mean aspen height	0.5472	8	Maximum aspen height	0.3712
9	Minimum stem-to-stem distance	–0.5024	9	Maximum aspen height	0.5192	9	Mean aspen height	0.330
10	Herb cover	0.4451	10	Herb cover	0.5022	10	Diameter of tallest aspen	0.3131
11	Mean aspen height	0.4419	11	Diameter of tallest aspen	0.4591	11	Shrub height	0.3102
12	Diameter of tallest aspen	0.4176	12	Minimum stem-to-crown distance	–0.2970	12	Minimum stem-to-crown distance	–0.2884
13	Herb height	0.3074	13	Shrub height	0.2605	13	Shrub cover	0.2651
14	Mean stem-to-crown distance	0.2929	14	Shrub cover	0.2182	14	Mean stem-to-stem distance	–0.2388
15	Minimum stem-to-crown distance	0.2303	15	Mean aspen diameter	–0.0998	15	Herb height	0.2238
16	Shrub height	0.1995	16	Maximum aspen diameter	0.0778	16	Mean stem-to-crown distance	–0.0721
17	Shrub cover	0.1552	17	Conifer cover	0.0769	17	Mean aspen diameter	–0.0629
18	Conifer cover	0.1490	18	Mean stem-to-stem distance	–0.0622	18	Herb cover	0.0284
19	Maximum aspen diameter	0.1096	19	Mean stem-to-crown distance	–0.0390	19	Conifer cover	0.0185
20	Mean stem-to-stem distance	0.0069	20	Herb height	–0.0149	20	Maximum aspen diameter	–0.0151

a Variables are ranked from 1 to 20 in order of decreasing absolute value for *R*.
b All variables relating to aspen include only aspen as tall or taller than the target pine (except "Total aspen cover").
c *R* is the Spearman's rank correlation coefficient. Negative correlations improve as *R* decreases from 0 to –1; positive correlations improve as *R* increases from 0 to +1.

TABLE A3.4 *Spearman's rank correlation coefficients for pairings of 1992 lodgepole pine height with vegetation abundance variables at the Moffatt, Meldrum, and Raven sites in the IDFdk subzone*

Moffatt			Meldrum			Raven		
Ranking of variables[a,b]		R[c]	Ranking of variables		R	Ranking of variables		R
1	Minimum stem-to-crown distance	0.5214	1	Total tree cover	0.5466	1	∑ aspen basal area	0.5581
2	Total tree cover	0.4975	2	Total aspen cover	0.5292	2	Tall aspen density	0.4975
3	Total aspen cover	0.4714	3	Maximum aspen height	0.4757	3	∑ stem-to-stem distance	0.4797
4	Tall aspen density	0.4357	4	∑ stem-to-stem distance	0.4567	4	Mean aspen height	0.4655
5	Minimum stem-to-stem distance	0.4086	5	Tall aspen density	0.4545	5	∑ stem-to-crown distance	0.4586
6	∑ stem-to-stem distance	0.3747	6	∑ aspen basal area	0.4535	6	Maximum aspen height	0.4581
7	∑ aspen basal area	0.3574	7	∑ stem-to-crown distance	0.4298	7	Total tree cover	0.4424
8	∑ stem-to-crown distance	0.3439	8	Mean aspen height	0.4212	8	Total aspen cover	0.4380
9	Maximum aspen height	0.3321	9	Minimum stem-to-crown distance	–0.3196	9	Minimum stem-to-stem distance	–0.4091
10	Mean stem-to-stem distance	–0.2578	10	Minimum stem-to-stem distance	–0.3122	10	Diameter of tallest aspen	0.3452
11	Conifer cover	0.2476	11	Herb height	0.2704	11	Minimum stem-to-crown distance	–0.2251
12	Mean stem-to-crown distance	–0.2352	12	Herb cover	0.2624	12	Maximum aspen diameter	0.1967
13	Herb cover	0.2155	13	Diameter of tallest aspen	0.2609	13	Herb height	0.1413
14	Diameter of tallest aspen	0.2133	14	Mean aspen diameter	–0.1937	14	Mean aspen diameter	0.1387
15	Maximum aspen diameter	0.1932	15	Mean stem-to-crown distance	0.1851	15	Mean stem-to-stem distance	–0.1125
16	Mean aspen height	0.1181	16	Shrub height	0.1421	16	Mean stem-to-crown distance	–0.0858
17	Shrub height	0.0977	17	Shrub cover	0.0966	17	Herb cover	–0.0806
18	Herb height	–0.0514	18	Mean stem-to-stem distance	0.0758	18	Shrub cover	0.0656
19	Mean aspen diameter	0.0061	19	Conifer cover	0.0409	19	Conifer cover	0.0381
20	Shrub cover	–0.0054	20	Maximum aspen diameter	0.0322	20	Shrub height	–0.0113

a Variables are ranked from 1 to 20 in order of decreasing absolute value for *R*.
b All variables relating to aspen include only aspen as tall or taller than the target pine (except "Total aspen cover").
c *R* is the Spearman's rank correlation coefficient. Negative correlations improve as *R* decreases from 0 to –1; positive correlations improve as *R* increases from 0 to +1.

TABLE A3.5 *Spearman's rank correlation coefficients for pairings of 1992 lodgepole pine leader length with vegetation abundance variables at the Hayfield, Two-mile, and Oie Lake sites in the SBSdw subzone*

Hayfield			Two-mile			Oie Lake		
Ranking of variables[a,b]		**R[c]**	**Ranking of variables**		**R**	**Ranking of variables**		**R**
1	Total tree cover	–0.4389	1	Mean stem-to-crown distance	–0.3609	1	Tall aspen density	–0.7262
2	Tall aspen density	–0.4228	2	∑ stem-to-crown distance	–0.3146	2	∑ stem-to-crown distance	–0.7240
3	Total aspen cover	0.4073	3	Herb cover	–0.2743	3	∑ stem-to-stem distance	–0.7230
4	∑ stem-to-stem distance	–0.4058	4	Tall aspen density	–0.2545	4	∑ aspen basal area	–0.7001
5	∑ aspen basal area	–0.3626	5	∑ stem-to-stem distance	–0.2542	5	Total aspen cover	–0.5934
6	Mean aspen diameter	0.3608	6	Mean aspen diameter	0.2220	6	Total tree cover	–0.5752
7	∑ stem-to-crown distance	–0.3524	7	Minimum stem-to-stem distance	0.1975	7	Diameter of tallest aspen	–0.5270
8	Maximum aspen height	–0.3340	8	Mean stem-to-stem distance	0.1624	8	Maximum aspen height	–0.4937
9	Shrub height	–0.2753	9	Shrub height	0.1612	9	Mean stem-to-crown distance	–0.4180
10	Minimum stem-to-crown distance	0.2494	10	Maximum aspen height	0.1578	10	Mean aspen diameter	0.4125
11	Diameter of tallest aspen	–0.2306	11	∑ aspen basal area	–0.1472	11	Minimum stem-to-stem distance	0.3096
12	Minimum stem-to-stem distance	0.1963	12	Total tree cover	–0.1349	12	Conifer cover	0.2902
13	Shrub cover	–0.1638	13	Shrub cover	–0.1310	13	Shrub height	–0.2667
14	Herb height	–0.1239	14	Total aspen cover	–0.1282	14	Maximum aspen diameter	–0.2075
15	Herb cover	–0.0772	15	Conifer cover	–0.1029	15	Minimum stem-to-crown distance	0.1905
16	Maximum aspen diameter	–0.0615	16	Minimum stem-to-crown distance	0.0931	16	Herb cover	0.1435
17	Mean stem-to-stem distance	–0.0292	17	Mean aspen height	0.0922	17	Herb height	–0.1224
18	Mean aspen height	–0.0277	18	Diameter of tallest aspen	–0.0404	18	Mean aspen height	–0.1181
19	Mean stem-to-crown distance	–0.0112	19	Maximum aspen diameter	–0.0175	19	Mean stem-to-stem distance	–0.0707
20	Conifer cover	–0.0019	20	Herb height	–0.0152	20	Shrub cover	–0.0534

a Vaariables are ranked from 1 to 20 in order of decreasing absolute value for *R*.

b All variables relating to aspen include only aspen as tall or taller than the target pine (except "Total aspen cover").

c *R* is the Spearman's rank correlation coefficient. Negative correlations improve as *R* decreases from 0 to –1; positive correlations improve as *R* increases from 0 to +1.

TABLE A3.6 *Spearman's rank correlation coefficients for pairings of 1992 lodgepole pine leader length with vegetation abundance variables at the Moffatt, Meldrum, and Raven sites in the IDFdk subzone*

Moffatt			Meldrum			Raven		
Ranking of variables[a,b]		*R*[c]	Ranking of variables		*R*	Ranking of variables		*R*
1	Tall aspen density	–0.6089	1	Tall aspen density	–0.5246	1	Tall aspen density	–0.5497
2	∑ stem-to-crown distance	–0.5810	2	∑ stem-to-stem distance	–0.5113	2	Mean aspen diameter	0.4955
3	∑ stem-to-stem distance	–0.5460	3	∑ stem-to-crown distance	–0.4954	3	∑ stem-to-stem distance	–0.4802
4	∑ aspen basal area	–0.4405	4	Mean aspen diameter	0.4495	4	∑ stem-to-crown distance	–0.4669
5	Total tree cover	–0.4156	5	∑ aspen basal area	–0.4477	5	Minimum stem-to-stem distance	0.4628
6	Total aspen cover	–0.4127	6	Mean stem-to-crown distance	–0.2812	6	∑ aspen basal area	–0.4410
7	Minimum stem-to-crown distance	0.3370	7	Minimum stem-to-crown distance	0.2600	7	Total aspen cover	–0.4104
8	Minimum stem-to-stem distance	0.2980	8	Shrub height	–0.2566	8	Minimum stem-to-crown distance	0.3939
9	Mean aspen diameter	0.2569	9	Minimum stem-to-stem distance	0.2520	9	Maximum aspen height	–0.3819
10	Herb height	–0.2457	10	Maximum aspen height	–0.2130	10	Total tree cover	–0.3579
11	Mean aspen height	0.1753	11	Total aspen cover	–0.1987	11	Mean stem-to-stem distance	0.3072
12	Maximum aspen height	–0.1664	12	Total tree cover	–0.1910	12	Mean aspen height	0.2066
13	Shrub height	–0.1130	13	Herb height	–0.1871	13	Conifer cover	–0.1746
14	Mean stem-to-crown distance	–0.0769	14	Maximum aspen diameter	–0.1861	14	Shrub cover	–0.1720
15	Diameter of tallest aspen	–0.0634	15	Herb cover	–0.1848	15	Shrub height	–0.1517
16	Mean stem-to-stem distance	0.0590	16	Mean stem-to-stem distance	–0.1539	16	Diameter of tallest aspen	–0.1044
17	Conifer cover	–0.0480	17	Shrub cover	–0.1284	17	Herb cover	0.0958
18	Herb cover	–0.0327	18	Conifer cover	0.1364	18	Mean stem-to-crown distance	–0.0466
19	Maximum aspen diameter	–0.0234	19	Mean aspen height	0.0997	19	Maximum aspen diameter	–0.0333
20	Shrub cover	0.0151	20	Diameter of tallest aspen	–0.0818	20	Herb height	0.0277

a Variables are ranked from 1 to 20 in order of decreasing absolute value for *R*.
b All variables relating to aspen include only aspen as tall or taller than the target pine (except "Total aspen cover").
c *R* is the Spearman's rank correlation coefficient. Negative correlations improve as *R* decreases from 0 to –1; positive correlations improve as *R* increases from 0 to +1.

TABLE A3.7 *Spearman's rank correlation coefficients for pairings of 1992 lodgepole pine stem diameter with various competition indices in the SBSdw (Hayfield, Two-mile, Oie Lake) and IDFdk (Moffatt, Meldrum, Raven) subzones*

SBSdw

Hayfield		Two-mile		Oie Lake	
Ranking of competition indices[a]	***R***[b]	**Ranking of competition indices**	***R***	**Ranking of competition indices**	***R***
1 Daniels (1976)	–0.8771	1 Navratil and MacIsaac (1993)	–0.8729	1 Lorimer (1983)	–0.9025
2 Braathe (1989)	–0.8721	2 Lorimer (1983)	–0.8009	2 Daniels (1976)	–0.8834
3 Lorimer (1983)	–0.8708	3 Daniels (1976)	–0.7697	3 Braathe (1989)	–0.8658
4 Navratil and MacIsaac (1993)	–0.8575	4 Braathe (1989)	–0.6791	4 Navratil and MacIsaac (1993)	–0.8656
5 Comeau, Braumandl, Xie (1993)	–0.8098	5 Comeau, Braumandl, Xie (1993)	–0.6293	5 Simard (1990)	–0.7987
6 Simard (1990)	–0.7862	6 Simard (1990)	–0.6186	6 Comeau, Braumandl, Xie (1993)	–0.7871
7 Wagner and Radosevich (1987)	–0.7809	7 Wagner and Radosevich (1987)	–0.5740	7 Wagner and Radosevich (1987)	–0.7334
8 DeLong (1991) (modified)	–0.6820	8 Brand (1986)	–0.4980	8 Brand (1986)	–0.6878
9 Brand (1986)	–0.6796	9 DeLong (1991) (modified)	–0.4975	9 DeLong (1991) (modified)	–0.6133
10 DeLong (1991)	–0.6079	10 DeLong (1991)	–0.4613	10 DeLong (1991)	–0.5211

IDFdk

Moffatt		Meldrum		Raven	
Ranking of competition indices	***R***	**Ranking of competition indices**	***R***	**Ranking of competition indices**	***R***
1 Navratil and MacIsaac (1993)	–0.8023	1 Navratil and MacIsaac (1993)	–0.7465	1 Daniels (1976)	–0.8076
2 Daniels (1976)	–0.7564	2 Lorimer (1983)	–0.7151	2 Lorimer (1983)	–0.7739
3 Lorimer (1983)	–0.7178	3 Daniels (1976)	–0.6770	3 Braathe (1989)	–0.7672
4 Braathe (1989)	–0.6360	4 Braathe (1989)	–0.6209	4 Simard (1990)	–0.7047
5 Simard (1990)	–0.5748	5 Comeau, Braumandl, Xie (1993)	–0.4977	5 Wagner and Radosevich (1987)	–0.6705
6 Wagner and Radosevich (1987)	–0.5714	6 Simard (1990)	–0.4936	6 Navratil and MacIsaac (1993)	–0.6678
7 Comeau, Braumandl, Xie (1993)	–0.5584	7 Wagner and Radosevich (1987)	–0.3996	7 Comeau, Braumandl, Xie (1993)	–0.6147
8 DeLong (1991)	–0.3615	8 Brand (1986)	–0.3751	8 Brand (1986)	–0.5054
9 DeLong (1991) (modified)	–0.3588	9 DeLong (1991)	–0.3283	9 DeLong (1991) (modified)	–0.4850
10 Brand (1986)	–0.3370	10 DeLong (1991) (modified)	–0.3110	10 DeLong (1991)	–0.4099

a Indices are ranked from 1 to 10 in order of decreasing absolute value for *R*.
b *R* is the Spearman's rank correlation coefficient. Negative correlations improve as *R* decreases from 0 to –1; positive correlations improve as *R* increases from 0 to +1.

TABLE A3.8 *Spearman's rank correlation coefficients for pairings of 1992 lodgepole pine height with various competition indices in the SBSdw (Hayfield, Two-mile, Oie Lake) and IDFdk (Moffatt, Meldrum, Raven) subzones*

SBSdw

Hayfield			Two-mile			Oie Lake		
Ranking of competition indices[a]		R[b]	Ranking of competition indices		R	Ranking of competition indices		R
1	Daniels (1976)	0.8040	1	Wagner and Radosevich (1987)	0.7719	1	Wagner and Radosevich (1987)	0.6852
2	Lorimer (1983)	0.7957	2	Daniels (1976)	0.7569	2	Simard (1990)	0.6834
3	Simard (1990)	0.7746	3	Simard (1990)	0.7568	3	Daniels (1976)	0.6752
4	Wagner and Radosevich (1987)	0.7198	4	Lorimer (1983)	0.7253	4	DeLong (1991) (modified)	0.6390
5	Braathe (1989)	0.7126	5	Braathe (1989)	0.6901	5	Lorimer (1983)	0.6388
6	Navratil and MacIsaac (1993)	0.6974	6	Navratil and MacIsaac (1993)	0.6838	6	DeLong (1991)	0.6304
7	Comeau, Braumandl, Xie (1993)	0.6479	7	Comeau, Braumandl, Xie (1993)	0.6504	7	Braathe (1989)	0.6113
8	DeLong (1991) (modified)	0.6111	8	DeLong (1991) (modified)	0.6912	8	Brand (1986)	0.5879
9	DeLong (1991)	0.5974	9	DeLong (1991)	0.6187	9	Comeau, Braumandl, Xie (1993)	0.5742
10	Brand (1986)	0.5754	10	Brand (1986)	0.5723	10	Navratil and MacIsaac (1993)	0.4951

IDFdk

Moffatt			Meldrum			Raven		
Ranking of competition indices		R	Ranking of competition indices		R	Ranking of competition indices		R
1	Daniels (1976)	0.5529	1	Wagner and Radosevich (1987)	0.5111	1	Daniels (1976)	0.5739
2	Navratil and MacIsaac (1993)	0.5468	2	DeLong (1991) (modified)	0.5079	2	Wagner and Radosevich (1987)	0.5603
3	Simard (1990)	0.5134	3	Brand (1986)	0.5033	3	Simard (1990)	0.5518
4	Braathe (1989)	0.4877	4	Comeau, Braumandl, Xie (1993)	0.4896	4	Lorimer (1983)	0.5508
5	Lorimer (1983)	0.4771	5	Daniels (1976)	0.4836	5	DeLong (1991)	0.4892
6	Wagner and Radosevich (1987)	0.4667	6	Simard (1990)	0.4772	6	Navratil and MacIsaac (1993)	0.4788
7	DeLong (1991)	0.4543	7	Lorimer (1983)	0.4675	7	Braathe (1989)	0.4762
8	DeLong (1991) (modified)	0.4128	8	Navratil and MacIsaac (1993)	0.4046	8	DeLong (1991) (modified)	0.4732
9	Comeau, Braumandl, Xie (1993)	0.3727	9	Braathe (1989)	0.4013	9	Brand (1986)	0.4145
10	Brand (1986)	0.3186	10	DeLong (1991)	0.3593	10	Comeau, Braumandl, Xie (1993)	0.4130

a Indices are ranked from 1 to 10 in order of decreasing absolute value for R.

b R is the Spearman's rank correlation coefficient. Negative correlations improve as R decreases from 0 to –1; positive correlations improve as R increases from 0 to +1.

TABLE A3.9 *Spearman's rank correlation coefficients for pairings of 1992 lodgepole pine leader length with various competition indices in the SBSdw (Hayfield, Two-mile, Oie Lake) and IDFdk (Moffatt, Meldrum, Raven) subzones*

SBSdw

	Hayfield			**Two-mile**			**Oie Lake**	
	Ranking of competition indices[a]	***R***[b]		**Ranking of competition indices**	***R***		**Ranking of competition indices**	***R***
1	Navratil and MacIsaac (1993)	–0.5358	1	Daniels (1976)	–0.3070	1	Lorimer (1983)	–0.8039
2	Comeau, Braumandl, Xie (1993)	–0.5220	2	Navratil and MacIsaac (1993)	–0.2821	2	Navratil and MacIsaac (1993)	–0.7796
3	Braathe (1989)	–0.4760	3	Lorimer (1983)	–0.2597	3	Braathe (1989)	–0.7777
4	Lorimer (1983)	–0.4735	4	Braathe (1989)	–0.2357	4	Daniels (1976)	–0.7546
5	Daniels (1976)	–0.4473	5	Simard (1990)	–0.2022	5	Comeau, Braumandl, Xie (1993)	–0.7146
6	DeLong (1991) (modified)	–0.3992	6	Wagner and Radosevich (1987)	–0.1905	6	Simard (1990)	–0.6853
7	Brand (1986)	–0.3992	7	Comeau, Braumandl, Xie (1993)	–0.1533	7	Wagner and Radosevich (1987)	–0.5985
8	Wagner and Radosevich (1987)	–0.3941	8	Brand (1986)	–0.1059	8	Brand (1986)	–0.5765
9	Simard (1990)	–0.3615	9	DeLong (1991) (modified)	–0.0946	9	DeLong (1991) (modified)	–0.4986
10	DeLong (1991)	–0.2759	10	DeLong (1991)	0.0344	10	DeLong (1991)	–0.3831

IDFdk

	Moffatt			**Meldrum**			**Raven**	
	Ranking of competition indices	***R***		**Ranking of competition indices**	***R***		**Ranking of competition indices**	***R***
1	Lorimer (1983)	–0.6602	1	Lorimer (1983)	–0.6307	1	Braathe (1989)	–0.6068
2	Navratil and MacIsaac (1993)	–0.6533	2	Braathe (1989)	–0.5980	2	Daniels (1976)	–0.6067
3	Daniels (1976)	–0.5647	3	Daniels (1976)	–0.5927	3	Lorimer (1983)	–0.6004
4	Braathe (1989)	–0.5293	4	Navratil and MacIsaac (1993)	–0.5783	4	Simard (1990)	–0.5301
5	Comeau, Braumandl, Xie (1993)	–0.5179	5	Simard (1990)	–0.4797	5	Comeau, Braumandl, Xie (1993)	–0.5183
6	Simard (1990)	–0.4528	6	Comeau, Braumandl, Xie (1993)	–0.3279	6	Navratil and MacIsaac (1993)	–0.4924
7	Wagner and Radosevich (1987)	–0.3383	7	Wagner and Radosevich (1987)	–0.2699	7	Wagner and Radosevich (1987)	–0.4882
8	Brand (1986)	–0.3308	8	Brand (1986)	–0.1920	8	Brand (1986)	–0.4296
9	DeLong (1991) (modified)	–0.3089	9	DeLong (1991) (modified)	–0.1360	9	DeLong (1991) (modified)	–0.3962
10	DeLong (1991)	–0.2674	10	DeLong (1991)	–0.0871	10	DeLong (1991)	–0.2770

a Indices are ranked from 1 to 10 in order of decreasing absolute value for *R*.

b *R* is the Spearman's rank correlation coefficient. Negative correlations improve as *R* decreases from 0 to –1; positive correlations improve as *R* increases from 0 to +1.

TABLE A3.10 *Spearman's rank correlation coefficients for pairings of percent light under the aspen canopy with various lodgepole pine growth variables in the SBSdw (Hayfield, Two-mile, Oie Lake) and IDFdk (Moffatt, Meldrum, Raven) subzones*

SBSdw

Hayfield		Two-mile		Oie Lake	
Ranking of growth variables[a]	**R**[b]	**Ranking of growth variables**	**R**	**Ranking of growth variables**	**R**
1 HDR	–0.6468	1 Basal area increment	0.5687	1 Stem diameter increment	0.6741
2 Basal area	0.6218	2 Stem diameter increment	0.5591	2 Stem diameter	0.6501
3 Stem diameter	0.6218	3 HDR	–0.5265	3 Basal area	0.6501
4 Basal area increment	0.6084	4 Basal area	0.4944	4 HDR	–0.6479
5 Stem diameter increment	0.5428	5 Stem diameter	0.4944	5 Crown width	0.6237
6 Crown width	0.4490	6 Crown length	0.4656	6 Basal area increment	0.5741
7 Crown length	0.3984	7 Crown width	0.3424	7 Crown length	0.5599
8 Leader length	0.3649	8 Leader length	0.2514	8 Leader length	0.5483
9 Height	0.2628	9 Height	0.0853	9 Height	0.4639

IDFdk

Moffatt		Meldrum		Raven	
Ranking of growth variables	**R**	**Ranking of growth variables**	**R**	**Ranking of growth variables**	**R**
1 Stem diameter increment	0.4942	1 Stem diameter increment	0.4940	1 Stem diameter	0.4699
2 Basal area increment	0.4244	2 Basal area increment	0.4924	2 Basal area	0.4669
3 Basal area	0.4281	3 HDR	–0.4620	3 Basal area increment	0.4699
4 Stem diameter	0.4281	4 Basal area	0.1990	4 HDR	–0.4802
5 Leader length	0.4249	5 Stem diameter	0.1990	5 Stem diameter increment	0.4515
6 Crown length	0.3960	6 Crown width	0.1583	6 Leader length	0.3302
7 Crown width	0.3606	7 Leader length	0.1583	7 Crown width	0.3224
8 Height	0.3158	8 Crown length	0.1408	8 Crown length	0.2754
9 HDR	–0.3148	9 Leader length	0.0039	9 Height	0.2229

a Variables are ranked from 1 to 9 in order of decreasing absolute value for *R*.
b *R* is the Spearman's rank correlation coefficient. Negative correlations improve as *R* decreases from 0 to –1; positive correlations improve as *R* increases from 0 to +1.

TABLE A3.11 *Spearman's rank correlation coefficients for pairings of PAR under the aspen canopy with various lodgepole pine growth variables in the SBSdw (Hayfield, Two-mile, Oie Lake) and IDFdk (Moffatt, Meldrum, Raven) subzones*

SBSdw

Hayfield		**Two-mile**		**Oie Lake**	
Ranking of growth variables[a]	**R**[b]	**Ranking of growth variables**	**R**	**Ranking of growth variables**	**R**
1 Stem diameter	0.6325	1 Stem diameter increment	0.5280	1 HDR	–0.5270
2 Basal area	0.6325	2 Basal area increment	0.5273	2 Stem diameter increment	0.5061
3 HDR	–0.6161	3 HDR	–0.5106	3 Crown width	0.4801
4 Basal area increment	0.5982	4 Basal area	0.4763	4 Leader length	0.4744
5 Stem diameter increment	0.5015	5 Stem diameter	0.4763	5 Basal area	0.4716
6 Crown width	0.4664	6 Crown length	0.4163	6 Stem diameter	0.4716
7 Crown length	0.4247	7 Crown width	0.3183	7 Crown length	0.4556
8 Leader length	0.3671	8 Leader length	0.2463	8 Basal area increment	0.4344
9 Height	0.3066	9 Height	0.0853	9 Height	0.3129

IDFdk

Moffatt		**Meldrum**		**Raven**	
Ranking of growth variables	**R**	**Ranking of growth variables**	**R**	**Ranking of growth variables**	**R**
1 Basal area	0.3665	1 Basal area increment	0.5178	1 Basal area increment	0.4677
2 Stem diameter	0.3665	2 HDR	–0.5124	2 Stem diameter increment	0.4629
3 Basal area increment	0.3611	3 Stem diameter increment	0.4945	3 HDR	–0.4611
4 Stem diameter increment	0.3577	4 Stem diameter	0.2460	4 Basal area	0.4275
5 HDR	–0.3555	5 Basal area	0.2460	5 Stem diameter	0.4275
6 Crown length	0.2893	6 Crown width	0.1830	6 Crown width	0.3157
7 Crown width	0.2805	7 Leader length	0.1575	7 Leader length	0.3086
8 Leader length	0.2792	8 Crown length	0.1408	8 Crown length	0.2580
9 Height	0.2156	9 Height	0.0039	9 Height	0.1933

a Variables are ranked from 1 to 9 in order of decreasing absolute value for *R*.

b *R* is the Spearman's rank correlation coefficient. Negative correlations improve as *R* decreases from 0 to –1; positive correlations improve as *R* increases from 0 to +1.

APPENDIX 4 LODGEPOLE PINE CONDITION AND DAMAGE FOR SBS AND IDF SITES IN 1999

TABLE A4.1 *Percentages of lodgepole pine with healthy foliage, leaders, and stems at the SBSdw and IDFdk sites in 1999*

	SBSdw			IDFdk		
Aspen density per 10-m² plot	**Foliage (%)**	**Leader (%)**	**Stem (%)**	**Foliage (%)**	**Leader (%)**	**Stem (%)**
0	90	90	90	89	100	84
1	82	91	73	90	80	60
2	77	54	62	92	92	42
3	88	63	75	100	100	88
4	77	77	62	88	63	50
5	84	47	53	100	60	60
6	89	22	22	100	78	67
7	86	57	71	75	50	50
8	75	0	50	86	71	86
9	33	67	67	80	60	100
≥ 10	50	30	50	68	46	50
Total	78	60	63	85	72	64

TABLE A4.2 *Percentages of lodgepole pine with whipping damage to foliage, leaders, and stems at the SBSdw and IDFdk sites in 1999*

	SBSdw			IDFdk		
Aspen density per 10-m² plot	**Foliage (%)**	**Leader (%)**	**Stem (%)**	**Foliage (%)**	**Leader (%)**	**Stem (%)**
0	0	0	0	0	0	0
1	0	9	9	0	10	30
2	0	39	31	8	8	50
3	0	38	25	0	0	0
4	0	23	31	0	38	38
5	0	53	37	0	40	40
6	0	78	67	0	11	22
7	0	43	29	0	25	38
8	0	75	50	14	29	14
9	0	17	17	20	40	0
≥ 10	0	60	40	7	36	36
Total	0	35	28	4	20	25

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